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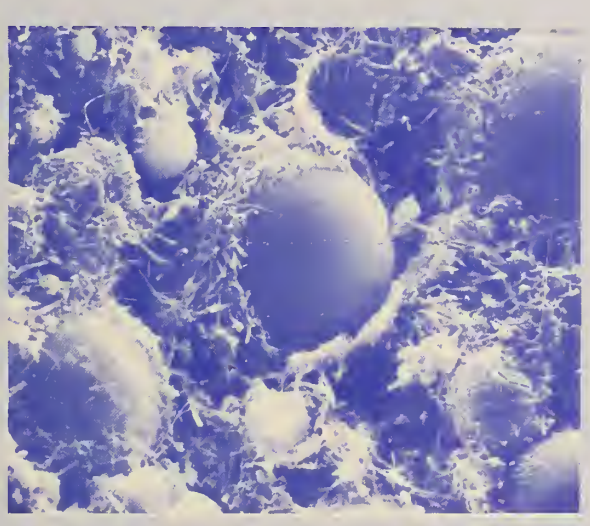
OF WASTE SULFATE FOR REMEDIAL TREATMENT OF SOILS

Vol. II. Appendixes



August 1976
Final Report

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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D. C. 20590

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16. Abstract

The effects of waste sulfate (phosphogypsum from fertilizer manufacture, flue gas desulfurization solids, and neutralized acid mine drainage solids) on physical and strength properties of soils have been studied. Waste sulfate alone has little effect on soil strengths. However, if it is used in combination with lime, higher strengths can be achieved with waste sulfate/lime than can be obtained with equivalent lime treatment because of soil-sulfate-lime reactions. Fly ash can be used with waste sulfate/lime mixtures to improve strengths further. Cement kiln dust has been shown to be an effective substitute for lime as a soil stabilizer.

The report is presented in two volumes. Volume I--Discussion of Results--describes the experimental work and contains the interpretation of data and conclusions and recommendations. Volume II--Appendixes--contains an annotated bibliography of literature reviewed, Atterberg Limit and moisture-density data for waste sulfate/soil systems, experimental unconfined compressive strength data, and an outline of multiple regression procedures used for data analysis.

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

This appendix consists of an annotated bibliography of literature collected during the first months of the subject study concerning use of waste sulfate for remedial treatment of soils. During the first 3 months of the program, several hundred abstracts dating back to 1940 were reviewed; from these, approximately 150 articles were retrieved. Subsequent to the retrieval, the articles were studied, sorted, abstracted, and about 100 are included in the annotated bibliography of this report. The review indicated that work prior to 1950 was adequately covered by post-1950 investigations. Consequently, early articles are not included in the annotated bibliography. In addition, some articles dealt primarily with agricultural soils, an area deemed to be peripheral to the main objectives of the program; and thus, they have not been included.

The literature review revealed that the reported information made more sense if evaluated chronologically. For this reason, the annotated bibliography is presented in a chronological format rather than alphabetically by author. A cross-index is presented in Table I correlating authors listed alphabetically and respective citation reference numbers.

The articles abstracted in the annotated bibliography fall into five general categories:

Soil Properties

Lime/Cement Soil Stabilization

Fly Ash Soil Stabilization

Sulfate Effects in Soil and Cement Properties

Other Soil Stabilization Systems

The references dealing with each of the above areas are presented in Table II. Reference numbers correspond to the specific citations in the annotated bibliography. In some cases, a single entry will appear in more than one column of Table II. In the case of lime/fly ash systems, however, the study is identified under "Fly Ash" only.

TABLE I

CROSS-INDEX OF AUTHORS AND CITATION REFERENCE NUMBERS

Author	Reference Number
Arman, Ara	70-1
Armstrong, T. C., Jr.	64-1
Barenberg, Ernest J.	67-1
Barksdale, Richard D.	68-1
Bensted, J.	73-1
Benton, Elton J.	60-1
Blaser, Harold D.	69-1
Chadda, L. R.	70-2
Clare, K. E.	51-1
Croft, J. B.	67-2
Davidson, D. T.	52-1, 58-1, 58-2
Diamond, Sidney	58-3
Djabarov, N.	63-1
Dong, S. B.	68-2
Dougan, Charles E.	69-2
Dumbleton, M. J.	66-1
Eades, James L.	66-2
El-Rawi, Nagih M.	68-3
Fujimasu, Jiro	72-1
Gambs, Gerard C.	66-3
George, K. P.	68-5
Gray, Donald H.	72-2
Gutt, W.	73-2
Handy, R. L.	58-4
Hauth, W. E., Jr.	51-2, 51-3
Hemwall, John B.	63-2
Hoekstra, Pieter	69-3
Hoover, J. M.	58-5
Hoskins, E. R.	70-3
Huang, Y. H.	68-6
Hughes, Michael L.	71-1
Ingles, O. G.	68-7
Ish-Shalom, M.	72-3
Jessberger, H. L.	70-4
Jones, Chester W.	58-6
Jones, D. Earl, Jr.	73-3
Jones, W. G.	58-7
Joshi, R. C.	74-1
Kaplar, Chester W.	70-5

TABLE I (concluded)

Author	Reference Number
Kenney, T. C.	67-3
Kondner, R. L.	62-1
Kozan, G. R.	63-3
Lafuma, H.	52-2
Lumb, Peter	67-4
Mainfort, R. C.	69-4
Marks, B. Dan	72-4
Mateos, Manuel	62-2, 62-3
Mehta, Povindar K.	64-2, 67-5, 73-4
Meikle, Phillip G.	72-5
Merill, D. C.	68-8
Midgley, H. G.	71-2
Miller, Richard H.	58-8
Minnick, L. John	51-4, 52-3, 70-6, 71-3, 73-4
Moulton, Lyle K.	73-6
Norling, L. T.	58-9
Radian Corporation	73-7
Ramsey, John P.	73-8
Redus, J. F.	58-10
Sheahan, J. M.	72-6
Sherman, George B.	71-4
Sherwood, P. T.	58-11, 61-1, 69-5
Smith, Wesley D.	70-7
Stocker, P. F.	63-4
Tenoutasse, N.	67-6
Thompson, M. R.	66-4
Thom, H. C. S.	70-8
Thornburn, Thomas H.	69-6
USDA	71-5
Varma, S. Prakash	73-9
Wang, Jerry W. H.	64-3
Watt, J. D.	66-5
Winterkorn, Hans F.	55-1
Wright, Paul J.	73-10
Wright, W.	57-1
Zube, Ernest	69-7

TABLE II

ANNOTATED BIBLIOGRAPHY CITATIONS IN SPECIFIC SUBJECT AREAS

Soil Properties	Lime/Cement Soil Stabilization	Fly Ash Soil Stabilization	Sulfate Effects on Soil and Cement Properties	Other Soil Stabilization Systems
51-2	51-1	51-4	52-2	68-7
51-3	58-3	52-3	58-11	69-4
52-1	58-4	57-1	63-1	69-5
55-1	58-6	58-1	63-2	69-6
62-1	58-7	58-2	64-1	70-7
67-2	58-9	58-5	64-2	71-7
67-3	58-10	58-8	67-5	72-1
67-4	61-1	60-1	67-6	73-8
68-2	62-3	62-2	68-1	
68-6	63-3	62-3	68-5	
69-3	63-4	66-1	69-1	
70-1	64-3	66-3	69-2	
70-4	66-2	66-5	70-3	
70-5	66-4	67-1	71-2	
70-8	68-3	70-6	71-3	
71-5	68-4	71-3	72-1	
73-3	68-5	72-5	72-3	
	68-7	73-3	73-1	
	68-8	73-6	73-2	
	69-7	74-1	73-4	
	70-2		73-5	
	70-3		73-7	
	71-4		73-9	
	72-4			
	72-6			
	73-10			

51-1 Clare, K. E., and A. E. Pollard, "The Relationship Between Compressive Strength and Age for Soils Stabilized with Four Types of Cement," Magazine of Concrete Research, 3(8), 57-64 (1951).

The relationships between unconfined compressive strength and age up to 28 days have been determined for soil-cement specimens made with sand, a silty clay, and a clay stabilized with four different cements. A comparison has also been made of the effects on compressive strength of coating test specimens with wax and of placing them in a humid atmosphere during the curing period.

51-2 Hauth, W. E., Jr., and D. T. Davidson, "Studies of the Clay Fraction in Engineering Soils: I. Identification by Differential Thermal Analysis," Proceedings of the Highway Research Board, 30, 449-458 (1951).

Differential Thermal Analysis (DTA) of soil samples may be a valuable tool for determining engineering behavior of soils, provided that the DTA samples are properly prepared. In some cases, the clay fraction of the soils must be concentrated by sieving soils through a 270 mesh screen and analyzing fines, or by extracting the < 1 μ particles by suspension/settling methods. Also, organic matter in soil should be removed with hydrogen peroxide treatment.

51-3 Hauth, W. E., Jr., and D. T. Davidson, "Studies of the Clay Fraction in Engineering Soils: II. Particle Size Distribution and Cation Exchange Capacity," Proceedings of the Highway Research Board, 30, 458-464 (1951).

This article presents methods for the determination of particle size distribution to below 0.1 μ, and for rapid determination of cation exchange capacity. At the time of publication, the authors recognized that these methods are valuable diagnostic tools, but were unable to correlate results with soil properties except in a very general manner.

51-4 Minnick, L. J., and R. H. Miller, "Lime-Fly Ash Compositions for Use in Highway Construction," Highway Research Board Proceedings, No. 30, 489-502 (1951).

A study has been made relating to the use of a group of lime-fly ash compositions in highway base construction. The use of small amounts of lime together with fly ash and aggregate materials including New Jersey Type A-3 soil, boiler slag, and crushed stone was considered. By carefully controlling the percentages of the ingredients, compositions have been produced which develop high compressive strength after aging for periods of 1 week or longer. Specimens subjected to wetting, drying, freezing and thawing tests indicate excellent performance when optimum quantities of lime and fly ash are employed. Field tests which have been started on the compositions developed in the laboratory indicate that the use of these test materials in the constructions of the base course of highways may give superior results at low cost.

52-1 Davidson, D. T., and J. B. Sheeler, "Clay Fraction in Engineering Soils: III. Influence of Amount on Properties," Proceedings of the Highway Research Board, 13, 558-562 (1952).

The authors have established an apparent linear relationship between the $< 2\ \mu$ content of soils with the following parameters: liquid limit, plastic limit, plasticity index, shrinkage limit, centrifuge moisture equivalent, hygroscopic moisture, field density, and field moisture content. No simple relationship was found between field-moisture equivalent and clay content.

52-2 Lafuma, H., "Expansive Cements," Paper Presented at Third Symposium on The Chemistry of Cement, London (1952).

Expansive cement is prepared from a ternary mixture of: (a) portland cement, which imparts its particular properties to the final product; (b) sulphoaluminate clinker, which is the expansion agent; and (c) blast-furnace slag, the stabilizing agent, the slow action of which enables the expansion to take place besides absorbing the excess sulphate of lime.

52-3 Minnick, L. J., and R. H. Miller, "Lime-Fly-Ash-Soil Composition In Highways," Proceedings of the Highway Research Board, No. 13 511-528 (1952).

Hydrated lime and fly ash have been found to be quite effective for the stabilization of various types of soil. An extensive study has shown that the improvement is developed in two ways. First, an immediate beneficial change is brought about in the engineering properties of the soil as evidenced by a marked reduction in plasticity index, an improvement in shrinkage and drainage characteristics, etc. Second, due to the cementing effect caused in part by the pozzolanic reaction between the lime and fly ash, the compositions upon aging develop relatively high compressive strength and good resistance to freezing, thawing, wetting and drying. Optimum proportions for the compositions are indicated by the use of compressive strength tests and by fundamental transverse frequency determinations. An investigation is also being made of a pulse velocity technique for evaluating the durability and field performance of the compositions.

55-1 "Soil and Soil-Aggregate Stabilization: A Symposium," Highway Research Board Bulletin, No. 108, January 11-14, 1955.

This document portrays the state of the art of soil stabilization as it stood in the mid-1950's. The emphasis of the symposium was to present the scientific facts and principles that have been applied and factors and phenomena that must be taken into account in the engineering application of soil stabilization methods. This document can serve as a basic reference of principles which must be dealt with in soil stabilization investigations. The papers presented at the symposium are presented below.

THE SCIENCE OF SOIL STABILIZATION, Hans F. Winterkorn

INHERITANCE FACTOR IN ORIGIN OF CLAY MINERALS IN SOIL, Franklyn B. Van Houten

ENGINEERING PEDOLOGY AND SOIL STABILIZATION, F. L. D. Wooltorton

SOIL STABILIZATION AND COLLOID SCIENCE, Ernst A. Hauser

PREDICTION OF THE CONSISTENCY LIMITS OF SOILS AND SOIL MIXTURES, Manuel Pimentel Periera dos Santos

EXCHANGE ADSORPTION BY CLAYS OF LARGE ORGANIC CATIONS, J. E. Gieseking

Discussion: Ernst H. Goebel

MICROBIOLOGICAL FACTORS IN SOIL STABILIZATION, P. C. T. Jones

STABILIZATION OF LATERITE SOILS, A. Remillon

SOIL STABILIZATION WITH LIME-FLY ASH MIXTURES: PRELIMINARY STUDIES WITH SILTY AND CLAYEY SOILS, T. Y. Chu, D. T. Davidson, W.L. Goecker, and Z. C. Moh

APPENDIX A: Development of Test Method for Preliminary Evaluation

APPENDIX B: Recommended Test Method for the Preliminary Evaluation of Lime-and-Fly Ash-Stabilized Silty and Clayey Soils

SOIL STABILIZATION WITH RESINS AND CHEMICALS, R. C. Mainfort

EFFECT OF CALCIUM ON THE CONTINUITY OF ELECTROOSMOTIC FLOW RATE, Ralph L. Rollins

ELASTIC BEHAVIOR OF SOIL-CEMENT MIXTURES, Friedrich Reinhold

FACTORS INFLUENCING PHYSICAL PROPERTIES OF SOIL-CEMENT MIXTURES, Earl J. Felt

STABILIZATION OF TENNESSEE GRAVEL AND CHERT BASES, E. A. Whitehurst

Discussion: Richard H. Miller

57-1 Wright, W., and P. N. Ray, "The Use of Fly Ash in Soil Stabilization," Magazine of Concrete Research, pp. 27-31, March 1957.

Since the war the demand for electricity has steadily risen, and in order to increase the efficiency of combustion to help meet this demand, modern power stations use pulverized coal. The burning of this pulverized coal by the power stations of this country produces large quantities of very fine ash, known as fly ash. Experiments using three different soils: sand, light clay, and heavy clay are described which suggest that fly ash can replace some of the cement normally used for soil stabilization.

58-1 Davidson, D. T., R. K. Katti, and D. E. Welch, "Use of Fly Ash with Portland Cement for Stabilization of Soils," Highway Research Board Bulletin No. 198, pp. 1-11 (1958).

It was concluded that fly ash is more promising as an additive to portland cement than as a replacement for part of the cement. The greatest benefits from fly ash appear to be obtainable with poorly graded, low clay soils such as dune sand. The role of fly ash appears to be due to greater surface area to promote cementation with the sand particles.

58-2 Davidson, D. T., J. B. Sheeler, and N. G. Delbridge, Jr., "Reactivity of Four Types of Fly Ash with Lime," Highway Research Board Bulletin, No. 193, pp. 24-31 (1958).

The pozzolanic activity of specific fly ashes is related to the carbon content of the ash and to its fineness. The upper limit of carbon content for good pozzolanic cementation is approximately 10%. The amount of fly ash passing a 325 mesh screen is inversely dependent on carbon content; thus, the finer the fly ash, the better the pozzolanic activity. Rates of pozzolanic reaction are dependent upon temperature and humidity conditions of the cure.

58-3 Diamond, S., and E. B. Kinter, "A Rapid Method of Predicting the Portland Cement Requirement for Stabilization of Plastic Soils," Highway Research Board Bulletin, No. 198, pp. 32-44 (1958).

The relation between the cement requirement of soil-cement mixtures and surface area (determined by the glycerol retention method) was investigated for a group of plastic soils, and a regressive equation and procedure were developed to predict cement requirement. Details of the prediction procedures are presented in the paper.

58-4 Handy, R. L., "Cementation of Soil Minerals with Portland Cement or Alkalis," Highway Research Board Bulletin, No. 198, pp. 55-64 (1958).

A hypothesis is advanced to explain long-term strength gains in soil-cement by readjustments within the mineral surface tending to improve chemical bonding. The hypothesis is extended to pozzolans and representative minerals in soils and in concrete, and offers an explanation of activation of silica by heat and by alkalis.

58-5 Hoover, J. M., R. L. Handy, and D. T. Davidson, "Durability of Soil-Lime-Fly Ash Mixes Compacted Above Standard Proctor Density," Highway Research Board Bulletin, No. 193, pp. 1-11 (1958).

The authors found that lime-fly ash stabilized soils (one sand, one silt, and one clay) developed increased durabilities when compacted to densities above optimum. Durability was determined by subjecting samples to various cycles of freeze-thaw and wet-dry and then measuring moisture absorption, swelling, and uncontinued compressive strength. Increases in strength during the wet-dry and freeze-thaw cycles are attributed to dissolution and reprecipitation of lime during the cycles.

58-6 Jones, C. W., "Stabilization of Expansive Clay with Hydrated Lime and with Portland Cement," Highway Research Board Bulletin, No. 193, pp. 40-47 (1958).

The paper describes results of laboratory results on a California expansive clay when stabilized with lime or portland cement. Although the cement admixture reduced soil shrinkage somewhat more than an equivalent amount of lime, the properties of the lime-treated soil were more favorable in other respects, i.e., reduction of plasticity and increase in unconfined compressive strength after wet-dry cycles.

58-7 Jones, W. G., "Lime-Stabilized Test Sections on Route 51, Perry County, Missouri," Highway Research Board Bulletin, No. 193, pp. 32-39 (1958).

Test sections were constructed by the Missouri State Highway Department to evaluate the effects of several types of lime for subbase stabilization. The limes used included: hydrated lime, quick lime, combination of hydrated lime and quick lime, and by-product waste from lime manufacture. It was found that hydrated lime gave the most satisfactory results. Waste lime gave the least satisfactory results, presumably because of the larger amounts (40%) of calcium carbonate in the material.

58-8 Miller, R. H., and W. J. McNichol, "Structure Properties of Lime-Fly Ash-Aggregate Compositions," Highway Research Board Bulletin, No. 193, pp. 12-23 (1958).

This study reports improved soil bearing properties when fly ash is included with lime as a stabilization agent. Improvement in strength is believed due to the pozzolanic action of the lime-fly ash mixture, creating a cementing process which will cause strength gains over several years. The experimental data were obtained with natural silts having an AASHTO classification of A-4.

58-9 Norling, L. T., and R. G. Packard, "Expanded Short-Cut Test Method for Determining Cement Factors for Sandy Soils," Highway Research Board Bulletin, No. 198, pp. 20-31 (1958).

A short-cut testing procedure is presented for determining current requirements for stabilization of sandy soils. The method is based upon the amount of soil material passing a No. 4 screen. Two methods are discussed: Method A is used for soils completely passing through No. 4 screen, while Method B is used for sandy soils in which some material is retained on the No. 4 screen.

58-10 Redus, J. F., "Study of Soil-Cement Base Courses on Military Airfields," Highway Research Board Bulletin, No. 198, pp. 13-18 (1958).

A group of military airfields with pavements comprised of soil-cement base courses and asphaltic-concrete surfacing were studied. The soils used in the soil-cement ranged from beach sand to lean clay. The investigation indicated that small percentages of cement tended to reduce plasticity in some borderline base-course materials, and aided construction with some cohesionless sands.

58-11 Sherwood, P. T., "Effect of Sulfates in Cement-Stabilized Clay," Highway Research Board Bulletin, No. 198, pp. 45-54 (1958).

This paper describes an investigation of the effects of sulfates on the strength of cement-stabilized clays. Magnesium sulfate in concentrations above 0.75% by weight in clay disintegrated when cement-stabilized clay was immersed in water. Calcium sulfate in concentrations greater than 1.0% reduced compressive strength, but strength reduction was lessened by increasing moisture content of the mix. Exposure of cement-stabilized specimen to aqueous sulfate solutions resulted in extensive degradation and loss of strength.

60-1 Benton, E. J., "Cement-Pozzolan Reactions," Highway Research Board Bulletin, No. 239, pp. 56-65 (1960).

Mixtures of calcium hydroxide, pozzolan, and water were reacted at 100°F for 1 to 6 months, and the reaction products were examined by X-ray diffraction and thermal analysis. The compounds identified included a poorly crystallized calcium silicate hydrate, tricalcium aluminum hexahydrate (or hydrogarnet), tetracalcium aluminate hydrate containing CO_2, and Stratling's quaternary compound. Mixtures of portland cement, pozzolan, and water under similar conditions yielded poorly crystallized calcium silicate hydrate, complex calcium aluminate hydrates containing SO_3 and/or CO_2, calcium hydroxide, and Stratling's compound. The reaction products obtained depended on the type of pozzolan and/or on the compositions of the portland cement.

61-1 Sherwood, P. T., "Soil Stabilization by the Use of Chemical Admixtures: A Review of the Present Position," Routes and Road Construction, 39, 102-111, April 1961.

This paper reviews the present state of knowledge concerning the application of chemical techniques to the modification of the properties of soil for road engineering. The treatment of soil with chemicals includes

the use of chemicals as stabilizing agents by themselves, as secondary additives to improve the efficiency of cement, lime and bitumen, and as soil conditioners, that is, agents which, when added to soil in small amounts, are able to change its texture. All three aspects of the chemical treatment of soil are considered, and the practical application of those materials that are economically acceptable are discussed.

62-1 Kondner, R. L., and J. R. Vendrell, Jr., "Clay Mineral Effect on the Stress-Strain Response of Soils in Direct Shear," Proceedings of Clay and Clay Mineral National Conference, Vol. 13, pp. 252-267 (1962).

More than 100 sets of direct shear tests were conducted on soils comprised of four references minerals and various combinations of the four reference materials. Experimental results agree quite well with hyperbolic stress-strain relation previously developed by the author. The hyperbolic stress-strain retention includes the Hvorslev strength parameters as experimental functions of clay mineral content.

62-2 Mateos, M., "Stabilization of Soils With Fly Ash Alone," Highway Research Board Bulletin, No. 335, pp. 59-64 (1962).

Fly ash reacts with lime to form a cementing material used to strengthen soils for the construction of bases and subbases for pavements. To sustain the cementitious reaction, lime must be added or supplied to the fly ash. Nevertheless, a survey of fly ashes revealed that some of them contain cementing materials--lime or other products--in a quality sufficient for good strength. The stabilization of soils with fly ashes that do not need added lime should be a very competitive method when the transportation cost of the fly ash is within economical limits. This paper presents the results obtained with several fly ashes used without lime to stabilize several soils with different textures.

62-3 Mateos, M., and D. T. Davidson, "Lime and Fly Ash Properties in Soil, Lime, and Fly Ash Mixtures; and Some Aspects of Soil-Lime Stabilization," Highway Research Board Bulletin, No. 335, pp. 40-64 (1962).

The best ratio of lime to fly ash, and the optimum amounts of lime and fly ash were dependent upon the kind of lime, fly ash, and soil used. Recommended amounts of lime and fly ash for different soils are presented. Dolomite monohydrate limes proved to be better than calcitic hydrated lime, although the calcitic lime is more beneficial in small amounts.

63-1 Djabarov, N., and W. Slatanov, "The Effect of Gypsum Upon the Strength of Sand-Lime Products," Zement-Kalk-Gips, 16, 104-107 (1963).

This study indicates that there is an optimum amount of gypsum that is needed for the stabilization of sand-lime products, and that the sand must contain argillaceous impurities. When such impurities are present, it was shown that products of significantly higher strengths could be made. The argillaceous impurities (Al_2O_3 and Fe_2O_3) are essential because without these oxides, no strength increase can take place when gypsum is added.

63-2 Hemwall, J. B., "Stabilization of Clay Soils and Aggregates--SO_4--PO_4," U.S. Patent 3,077,740, assigned to Dow Chemical Company, February 19, 1963.

It has been discovered that the incorporation in argillaceous soils of orthophosphoric acid (H_3PO_4) and sulfuric acid (H_2SO_4) together provides a composition which may be compacted to produce a stabilized mass having significantly improved compression strength as compared to untreated argillaceous soils.

63-3 Kozan, G. R., and W. B. Fenwick, "Investigations of a Chemically Modified Quicklime as a Stabilizing Material," U.S. Army Engineer Waterways Experiment Station Technical Report No. 3-455, Report No. 6, June 1963.

This report summarizes the results of laboratory and field investigations to evaluate a chemically modified quicklime as a soil stabilizer for moderately wet, fine-grained soils.

63-4 Stocker, P. F., "The Chemical Aspects of the Cement Stabilization of Heavy Clays," Construction Review, 36, 13-22, September 1963.

Properties of clays and portland cement hydratic products are discussed. These properties have been used as the basis for postulating mechanisms for the stabilization processes involved in clay-cement stabilization. The need for modification of this type of analysis is shown, together with modified versions of the mechanisms.

64-1 Armstrong, T. C., and B. M. Whitehurst, "Sulfoaluminate Cement," U.S. Patent 3,147,129, Assigned to Socony Mobil Oil Company, Issued September 1, 1964.

A uniform, high strength sulfoaluminate cement can be prepared by combining a pulverized calcium aluminate slag, a pulverized substantially neutral anhydrite prepared from natural or by-product gypsum, and a suitable additive such as a mixture of sugar, lime and silica.

64-2 Mehta, P. K., and A. Klein, "Investigations on the Hydration Products in the System $4CaO \cdot 3Al_2O_3 \cdot SO_3$ - $CaSO_4$ - CaO-H_2O," Highway Research Board Special Report, No. 90, pp. 328-352 (1964).

Investigations on early age hydration products of compositions made with varied properties of $4CaO \cdot 3Al_2O_3 \cdot SO_3$, $CaSO_4$, and CaO were done to identify the nature and amounts of hydrates formed at intervals of 6, 12, 24, 48, and 72 hr. In most cases, the trisulfate hydrate, $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$ (ettringite) was observed to be the stable phase except where the CaO/SO_3 molar ratio exceeded 4.0, and the Al_2O_3/SO_3 molar ratio exceeded 1.0. In these cases, a monosulfate hydrate of approximate composition $3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 18H_2O$ was found to be the stable phase. Ettringite is the substance responsible for expansive properties in expansive cement.

64-3 Wang, J. W. H., and R. L. Handy, "The Role of MgO in Soil-Lime Stabilization," Highway Research Board, Special Report No. 90, pp. 475-492 (1964).

Results reported in this paper are intended to explain why dolomitic limes are more effective in producing strength when mixed with soils as compared to high-calcium limes. Results indicate that hydration of MgO to $Mg(OH)_2$ occurs faster than lime-clay pozzolanic reactions at room temperature. At higher temperature (> 40°C, 104°C), pozzolanic reactions mask cementation effects of magnesia. Dolomitic lime thus may be used to advantage in cool climates or late in the construction season.

66-1 Dumbleton, M. J., P. T. Sherwood, and G. E. Bessey, "The Use of Lime and Mixtures of Lime and Pulverized Fuel Ash for Soil Stabilization in Britain," Chemistry and Industry, pp. 1777-1787, October 22, 1966.

Soil stabilization is the treatment of locally occurring natural materials to make them suitable for use in the road structure. In Great Britain there are considerable areas in which the soils are unsuitable

for use in the form in which they occur, but on the other hand good quality roadmaking materials are rarely far away. Lime and mixtures of lime and pulverized fuel ash have been used as stabilizing agents in other parts of the world, and part of the program of research at the Road Research Laboratory has been to evaluate the potential uses of these methods for soil stabilization in Great Britain. The results of this work are summarized in this paper.

66-2 Eades, J. L., and R. E. Grim, "A Quick Test to Determine Lime Requirements for Lime Stabilization," Highway Research Board Bulletin, No. 139, pp. 61-72 (1966).

As lime is consumed in the stabilization of soils, the pH of the system will drop. A method for determining lime requirements has been developed in which sufficient lime is added to maintain lime-soil slurry pH at 12.3 for 1 hr. If pH drops below 12.3, then more lime is needed.

66-3 Gambs, G. C., "Marketing Fly Ash--U.S. and European Programs," Coal Age, 71, 86-92 (1966).

An assessment of the progress in the commercial utilization of fly ash, by the countries of Europe, to determine if these programs can be successfully exploited in the U.S. is the subject matter of the article. The important markets discussed are: (a) fly ash for structural fill; (b) fly ash either in the manufacture of a portland-pozzolan cement, or directly in the concrete mix as a partial replacement of standard cement; and (c) utilization of fly ash in the manufacture of lightweight aggregate.

66-4 Thompson, M. R., "Shear Strength and Elastic Properties of Lime-Soil Mixtures," Highway Research Board, Bulletin No. 139, pp. 1-14 (1966).

Results of the study indicate that: (a) lime treatment substantially increases the shear strength of lime-reactive soils; (b) moduli of elasticity of lime-soil mixtures are larger than those of untreated soils; and (c) increased curing periods produced lime-soil mixtures with higher shear strengths and elastic moduli. In typical flexible pavement structures, the shear strengths of the mixtures were sufficient to prevent shear failure of the lime-stabilized layer.

66-5 Watt, J. D., and D. J. Thorne, "The Composition and Pozzolanic Properties of Pulverized Fuel Ashes," J. Appl. Chem., 16, 33-39 February 1966.

The pozzolanic activities of fly ashes and other materials have been examined. The activity can be determined by two chemical methods based on estimating the amount of acid-soluble material that is produced when a pozzolan reacts with lime. The conclusions reached from these results, on the relative importance of the factors that determine the activity of an ash, agree with those based on the crushing strengths of fly ash mortars. There was a close relation between the amount of chemical reaction taking place in a mortar and the strength it developed, but short-term chemical assessments showed no relation to long-term crushing strengths. It was concluded that chemical methods were unlikely to have any practical value for predicting the long-term strength of a mortar in the field.

67-1 Barenberg, E. J., "Lime-Fly Ash-Aggregate Mixtures," U.S. Bureau of Mines Information Circular, No. 8348, pp. 111-134 (1967).

The paper discusses a research study initiated at the University of Illinois by Professor George Hollon in March 1956, on mixtures of lime, fly ash, and aggregate under the sponsorship of the Illinois Division of Highways. During that period, a definite need for establishing a pavement design criterion for lime-fly ash-aggregate bases became evident. A research program to satisfy this need was initiated in July 1959. Its primary objective was to develop sufficient information so that a structural design procedure could be formulated for pavements with lime-fly ash-aggregate bases.

67-2 Croft, J. B., "The Influence of Soil Mineralogical Composition on Cement Stabilization," Geotechnique, 17, 119-135 (1967).

A series of studies is described in which various mineralogical components of soils on cement stabilization were investigated. Explanations are advanced for the changes in physical properties and development of strength in compacted mixtures. It was found that soils characterized by montmorillonite, some mixed-layered clays, and degraded weathering products retard the hydration of cement and are more suitably stabilized by lime. Kaolinitic and illitic soils on the other hand are inert and can be economically stabilized with cement.

67-3 Kenney, T. C., "The Influence of Mineral Composition on the Residual Strength of Natural Soils," Proceedings of the Geotechnical Conference on Shear Strength Properties of Natural Soils and Rocks, Oslo, Norway, pp. 123-128 (1967).

Drained direct-shear tests on natural soils, pure minerals, and mineral mixtures have shown that residual shear strength is primarily dependent on mineral composition, and is not related to plasticity or grain-size characteristics. Massive minerals (quartz, feldspar, and calcite) exhibit greatest stress ratios, $t_g \Phi_{res} > 0.58$. Micaceous minerals (hydrous mica and perhaps illite) exhibit $t_g \Phi_{res} > 0.30$. Montmorillonite minerals are the weakest having stress ratios < 0.20.

67-4 Lumb, P., "The Variability of Natural Soils," Canadian Geotechnical Journal, 3(2), 74-97 (1967).

The variation in properties of four natural soils can be used as a rational basis for the choice of design parameter. The choice criterion is the probability that the parameter is less than the design value. Properties include: Atterberg limits, grading, strength, and compressibility. In the case of bearing capacity estimates, an analysis of the conventional safety factor suggests that a suitable value of probability or "risk" of failure for design is of the order of 0.01 or 0.001%.

67-5 Mehta, P. K., and A. Klein, "Formation of Ettringite in Pastes Containing Calcium Aluminoferrites and Gypsum," Highway Research Board Record, No. 192, pp. 36-45 (1967).

This study indicates alumina tied up in the alite phase of portland cement does not liberate alumina which can be used for the formation of ettringite during cement hydration. On the other hand, alumina in calcium aluminoferrite phase of cement was readily available for ettringite formation, when the cement is reacted with water and gypsum.

67-6 Tenoutasse, N., "Investigation Into the Kinetics of the Hydration of Tricalcium Aluminate in the Process of Calcium Sulfate and Calcium Chloride," Zement-Kalk-Gips, 70, 459-467 (1967).

Calcium chloride accelerates the reaction between tricalcium aluminate and gypsum. The sulfate ions react preferentially with the aluminate in the presence of chloride. Ettringite formed by this reactive remains stable as long as the liquid phase contains calcium chloride.

68-1 Barkstale, R. D., and R. P. Vergnalle, "Expansive Cement Stabilization of Bases," Highway Research Board Record, No. 255, pp. 30-41 (1968).

The use of expansive cements (a mixture of portland cement, calcined bauxite, and gypsum) is a new approach to the problem of controlling shrinkage cracks in soil-cement stabilized bases. This paper reports that the use of Chem Comp, a proprietary expansive cement, will result in a definite reduction and in some cases elimination of shrinkage cracks when used to stabilize a micaceous silty sand, where used in conjunction with Type I portland cement. Beneficial effects were particularly encouraging at moisture contents of 3% above optimum.

68-2 Dong, S. B., C. Hasson, and R. A. Westerman, "Embankment Analysis and Field Correlation," Highway Research Board Record, No. 223, pp. 9-17 (1968).

Computer numerical analyses for particular embankments in California were compared with field measurements in order to assess the accuracy of the mathematical model and prediction technique. Results indicated that the model can lead to qualitative predictions, but is not entirely satisfactory for quantitative predictions.

68-3 El-Rawi, N. M., T. A. Halliburton, and R. L. Jones, "Effect of Compaction Methods on Strength Parameters of Soil-Cement Mixtures," Highway Research Board Record, No. 255, pp. 72-80 (1968).

Two compaction methods, impact and kneading, were used to study the effect of compaction method on strength of soil-cement mixtures. Parameters evaluated were Φ, angle of internal friction, and c, cohesion. For all practical purposes, Φ values were not influenced by compaction method, cement content, or age. However, it was found that for granular soil-cement mixtures, specimens evaluated by impact compaction yielded high c values; and for silt-cement mixtures, specimens molded by kneading gave higher c-values.

68-4 George, K. P., "Shrinkage Characteristics of Soil-Cement Mixtures," Highway Research Board Record, No. 255, pp. 42-58 (1968).

For the soils studied,, total shrinkage appeared to be a function of the amount and kind of clay in the soil, with montmorillonite contributing more than other types. Shrinkage can be reduced considerably by compacting to higher densities, and appears to be caused by loss of moisture.

68-5 George, K. P., "Cracking in Cement-Treated Bases and Means for Minimizing It," Highway Research Board Record, No. 255, pp. 59-71 (1968).

Experimental results show that crack spacing is mainly a function of the tensile strength of treated soil. Soil cracks are caused by shrinkage forces between soil aggregate particles which overcome tensile strengths and result in separation of soil aggregate. Additives were studied to reduce shrinkage. Lime and fly ash proved to be the best, followed by sulfates of magnesium, sodium, and calcium; and expansive cement.

68-6 Huang, Y. H., and F. D. Shepard, "Laboratory Investigation of the Use of High Moisture Content Soils in High Fills," Highway Research Board Record, No. 223 (1968).

The purpose of this study was to investigate (a) the effect of thixotropy, initial moisture content, density, and consolidation in shear strength of clayey soils with moisture contents 8% above optimum; (b) the effect of initial moisture content and density on the consolidation characteristics of these soils; and (c) the possibility of using these soils in high fills and the manner in which they should be used. Results indicate that when a soil is consolidated under high pressures, the initial moisture content and density have little effect on final shear strengths.

68-7 Ingles, O. G., "Advances in Soil Stabilization," Rev. Pure and Applied Chem., 18, 291-310 (1968).

The modification of soil to meet specific engineering requirements for soil stabilization requires a detailed appreciation of many diverse soil properties, both original and requisite, and thereby relies on data from a wide variety of disciplines, chemical, physical, and mechanical, to indicate by broad group only. Such information tested against the conditions and limitations of actual field practice is the subject matter of this paper.

68-8 Merrill, D. C., and J. M. Hoover, "Laboratory Freeze-Thaw Tests Of Portland Cement-Treated Granular Bases," Highway Research Board Record, No. 255, pp. 16-29 (1968).

A new procedure developed at Iowa State University for conducting freeze-thaw tests of cement-treated soils is presented. In the Iowa test, the sample is undisturbed between cycles and is frozen from the top down with water continually available at the base of the specimen. In addition, samples are prepared by a vibrating compaction procedure rather than by the standard Proctor compaction method. The Iowa freeze-thaw test is easier to conduct and more nearly duplicates field conditions of freezing and thawing than does the ASTM test.

69-1 Blaser, H. D., and O. S. Scherer, "Expansion of Soils Containing Sodium Sulfate Caused by Drop in Ambient Temperature," National Research Council, No. 1641, pp. 150-160 (1969).

Soils containing over 0.2% Na_2SO_4 in solution and 15% or more minus 5 μ fractions tend to heave if ambient temperature varies between 35 and 100°F, and if ample soil moisture is available. Treatment with calcium chloride or phosphoric acid does not always provide permanent cures to the salt heaving problem, since sulfates in underlying soils may eventually rise to the surface and recreate the salt heaving.

69-2 Dougan, C. E., "An Experimental Salt-Stressing Concrete Pavement: II. Four Year Pavement Evaluation," Highway Research Board Record, No. 291, pp. 14-31 (1969).

This report deals with the 4-year evaluation of a test section of pavement in Connecticut made from expansive cement. Early construction difficulties and pavement distress appeared to have significantly affected the pavement performance. Transverse cracking that developed was probably related to insufficient prestress in the concrete slabs. The data suggest that the test slabs performed in a manner similar to continuously reinforced concrete pavements.

69-3 Hoekstra, P., "The Physics and Chemistry of Frozen Soils," National Research Council, No. 1641, pp. 78-90 (1969).

Engineering properties of frozen soils are affected by the phase composition of the water in the soil, i.e., the ratio of unfrozen water to ice. The main factors in determining this ratio are temperature, surface area, and salt content; minor factors include mineralogical composition, structure, and pressure. The ratio of unfrozen water to ice in soils can be calculated using a thermodynamic approach involving swelling pressure data for clays and moisture characteristic curves for granular soils. Calculated data are in good agreement with experimental data.

69-4 Mainfort, R. C., "Stabilization of Base Course Aggregates with Rock Salt," Highway Research Board, No. 294, pp. 23-45 (1969).

A 9-year evaluation of test sections in Michigan indicates that aggregate containing up to 12% fines can be successfully used in base course construction when treated with rock salt. Salt-treated aggregate handled and compacted best when moisture contents were 1 to 2% below optimum. Salt content diminished to a constant value in the high-fines sections with time; salt was virtually all leached out in 3 years in low-fines sections. Excellent adhesive between asphalt and salt-treated bases was obtained.

69-5 Sherwood, P. T., and R. G. Pocock, "The Utilization of Cement-Stabilized Waste Materials in Road Construction," Roads and Road Construction, 47, 43-50, February 1969.

It is in the national interest to make use of low-grade and waste materials for road construction as this conserves the supplies of good quality roadmaking materials and assists in problems arising from the disposal of unwanted materials. In addition economic considerations make it likely that the cost of aggregates will increase in those areas where they are already in short supply, whereas low-grade and waste materials are by their very nature available at low cost.

The study considers the extent to which the road construction industry can use low-grade and waste materials for base and subbase construction. It discusses the advantages and disadvantages of the use of such materials on practical, economic and aesthetic considerations. Four groups of materials--chalk, pulverized fuel ash, colliery shale, and quarry wastes are dealt with in detail. They all occur in large quantities and when stabilized with cement they can all be made suitable for use in road pavement construction.

69-6 Thornburn, T. H., and R. Muro, "Stabilization of Soils with Inorganic Salts and Bases: A Review of the Literature," Highway Research Board Record, No. 294, pp. 1-22 (1969).

This report consists of an annotated bibliography of the important literature on soil and aggregate stabilization with inorganic salts and bases published prior to 1965. In all, approximately 70 references of the 800 to 1,000 available have been reviewed, among which are several bibliographies providing additional references. From the more informative references, the authors have attempted to summarize information on stabilizer properties, mechanics of stabilization, properties of the stabilized soil, construction methods, field results, and the use of secondary additives. Particular attention is devoted to stabilization with sodium chloride, calcium chloride, and sodium hydroxide, which are the only salts and bases that have been evaluated sufficiently to draw meaningful conclusions.

69-7 Zube, E., et al., "Service Performance of Cement-Treated Bases as Used in Composite Pavements," Highway Research Board Record, No. 291, pp. 57-69 (1969).

One hundred seventy-five cement-treated base (CTB) composite pavements with varying cement contents built between 1950 and 1962 were evaluated; 64% had given excellent service, 17% were rated good, 8% were rated fair, and 11% required extensive maintenance early in their design lives. The main causes of failure appeared to be insufficient cement content, poor mixing of cement, excessive trimming of the compacted CTB, insufficient CTB thickness, inadequate CTB compaction, or deficiencies in the asphalt concrete surfacing thickness or quality.

A significant improvement in the performance of CTB composite pavements was attributed to extending the CTB at least 1 ft into the shoulder; plant-mixing the CTB; building the project in a temperate climate; increasing the thickness of the asphalt, concrete surfacing; limiting the compacted thickness of any one layer of CTB to 0.50 ft; using Type II rather than Type I cement, using a minimum CTB thickness of 0.50 ft; and providing a minimum in-place CTB compressive strength of 500 psi.

70-1 Arman, A., "Engineering Classification of Organic Soils," Highway Research Record, No. 310, pp. 75-89 (1970).

A correlation was established between water content, water absorption, and pH of organic soils. It was found further that methods for determining organic contents of soils were in error. Organic content should be determined by combustion of 440°C rather than 950°C. It was concluded that from an engineering standpoint, the character, source, or environment of the organic matter in soils is of secondary importance. Moisture absorption, specific gravity, and permeability are of primary importance in characterizing organic soils. A new classification based on characteristics of organic soils is presented.

70-2 Chadda, L. R., "Laboratory Studies on the Stabilization of Clays At High Moisture for Emergent Road Construction," Roads and Road Construction, 48, 177-179, June 1970.

Addition of 5 to 7% hydrated lime to montmorillonitic soils in India having moisture contents of 50 to 55% has resulted in rapid development of strength without mechanical compaction. Illitic clays and alluvial soils require that 20 to 30% reaction pozzolana, e.g., fly ash, be mixed with the lime for rapid development of strength in saturated conditions.

70-3 Hoskins, E. R., and D. W. Hammerquist, "Investigation of Alternative Chemical Treatments for Controlling Expansive Soil in Roadways in Western South Dakota," South Dakota School of Mines and Technology, Final Report on HP5898(04), PB 199 099, October 1970.

The effect of locally available additives in the swelling of Pierre Shale was determined. The additives included: lignite, gypsum, slime tailings from Homestake Mining Company's Mill (gold recovery), kiln dust from the State Cement Plant (Rapid City), and an inert grit. The additives were compared against standard lime stabilization. Lime was most effective, followed by the lignite and slime tailings. Kiln dust proved to be more effective than the gypsum and the inert grit, but less effective than the lignite or slime tailings.

70-4 Jessberger, H. L., and D. L. Carbee, "Influence of Frost Action on the Bearing Capacity of Soils," Highway Research Board Record, No. 304, pp. 14-26 (1970).

A procedure for determining the reduction of bearing capacity of subgrade soil or subbase materials because of freeze-thaw cycles has been developed. The procedure is useful for all soil types except clays. The procedure consists of California Bearing Ratio (CBR) tests on soil samples subjected to several freeze-thaw cycles. It has been found that the CBR value after several freeze-thaw cycles is controlled by the fraction of particles less than 20 μ and the coefficient of uniformity.

70-5 Kaplar, C. W., "Phenomenon and Mechanism of Frost Heaving," Highway Research Board Record, No. 304, pp. 1-13 (1970).

This paper presents a mechanistic explanation of first action in soils based upon the hypothesis that liquid films existing between particles and an ice lens are the focal centers of energy for soil heaving. Typical experimental data are presented illustrating the reduction of heave rate with increased external and internal resistance. Changes in frost heaving rates can be affected by addition or removal of either or both coarse aggregate or soil fines. Suggestions are offered for modifying soil to reduce heaving by altering ratios of coarse to fine materials.

70-6 Minnick, L. J., "Lightweight Concrete Aggregate From Sintered Fly Ash," Highway Research Board Record, No. 307, pp. 21-32 (1970).

Lightweight concrete aggregate is being produced commercially from pulverized coal fly ash by several plants. The type of fly ash used in the manufacturing process is generally that produced from bituminous coal. The characteristics of fly ash that are required in the forming and sintering process are described. A description of the physical properties of the fly ash aggregate is presented. The evaluation of these aggregates by the use of ASTM methods gives a good indication of the performance of the various materials in structural concrete. Comparisons are provided between other types of lightweight aggregate concrete, and in all cases, the fly ash concrete shows a favorable range of properties. Of significance in making comparisons is the high rate of absorption of the aggregate, the residual pozzolanic activity, and the relatively low cement factors required for lean concrete. Information is presented on typical mix designs for use in structural concrete.

70-7 Smith, W. D., "Chemical Stabilization Improves County's Roads," Better Roads, 40, 18-20, April 1970.

The article discusses the chemical stabilization of surface roads in Webster City, Iowa. These surfaces are constructed in several different ways: prewetted and mixed in a pugmill, wetted and blade-mixed on the road, calcium chloride added at the pugmill or on the road, laid down by a Jersey spreader or by a blade. They conclude that a stabilized surface will stand up under heavy traffic and extremely adverse weather and soil conditions much better than a normal gravel or rock surface will.

70-8 Thom, H. C. S., "Quantitative Evaluation of Climatic Factors in Relation to Soil Moisture Regime," Highway Research Record, No. 301, pp. 1-4 (1970).

The author suggests that hourly precipitation data can be used to predict subgrade moisture variations and has developed some empirical relationships that could be useful in preliminary studies.

71-1 Hughes, M. L., and T. A. Halliburton, "Use of Zinc Smelter Waste as Highway Construction Material," Highway Research Record, No. 430, pp. 16-25 (1971).

Zinc smelter wastes (smelter tailings) will achieve satisfactory stability values when modified by addition of fine sand or when separated or crushed and recombined to meet particular gradative requirements. The wastes so treated are suitable for sand-asphalt mixes, and should enhance skid resistance properties of asphaltic concrete surfaces. Transportation costs for these materials make these uneconomical for use at points distant from their stock piles. However, the zinc smelter wastes should be attractive to small municipal and county road building agencies in the vicinity of zinc smelter waste stockpiles.

71-2 Midgley, H. G., and K. Pettifer, "The Micro Structure of Hydrated Super Sulfated Cement," Cement and Concrete Research, 1, 101-104 (1971).

Mineralogical examination of the setting of super sulfated cement has shown that the rapid increase in strength up to about 7 days is due to the formation of large lath-like crystals of ettringite. The subsequent, but slower, increase in strength is due to the formation of both granular and plate-like calcium silicate hydrate.

71-3 Minnick, L. J., "Structural Compositions Prepared from Inorganic Waste Products," Paper presented at the Annual Meeting of the AASHO, Miami Beach, Florida, December 5-10, 1971.

This paper presents technical aspects of aggregates made from limes, sulfate waste, and fly ash. The reaction chemistries involve (a) the reaction of lime with acidic or soluble sulfates to encapsulate free water and soluble constituents in the waste, (b) the reaction of the lime/sulfate with ion oxide and alumina, and (c) pozzolanic reactions between lime and fly ash.

71-4 Sherman, G. B., et al., "The Relative Stabilizing Effect of Various Limes on Clayey Soils," California State Division of Highways, PB 204370, September 1971.

The effects of two hydrated limes and three quicklimes as the uncombined compressive strengths of three different soils are discussed. Effects of lime gradation and calcium hydroxide content were also studied. Correlations were established between lime gradation and compactability, and between specimen density and compressive strengths.

71-5 U.S. Department of Agriculture, Soil Conservation Service, "Guide for Interpreting Engineering Uses of Soils," U.S. Government Printing Office, Washington, D.C., November 1971.

This memorandum outlines procedures and guidelines which local soil scientists are to use in making engineering interpretations of soils for inclusion in published soil surveys. It sets forth the information the engineering section in the survey should contain and suggests a format that helps to maintain consistency in the presentation of engineering interpretations. The objective of these guidelines is to make the soil surveys more easily understandable to the users of the surveys.

72-1 Fujimasu, J., "Hydraulic Composition," U.S. Patent No. 3,642,509, assigned to Fujimasu Industries International, February 15, 1972.

This invention relates to earth control and more particularly, to stabilizing or solidifying earth. The agent appears to be similar in composition to expansion cement, except that alkaline earth chlorides and silicofluorides are added, as well as alkali carbonate, buffering agent and lignin sulfonate. It discusses a soil-setting agent which is useful in connection with a variety of soils and soil conditions. Some characteristics of the soil-setting agent are: high compressive strength,

rapid setting time, good dimensional stability, high crack, weather and wear resistance, and some elasticity.

72-2 Gray, D. H., and Y. K. Lin, "Engineering Properties of Fly Ash," J. Soil Mechanics and Foundations Div., Proceedings of the ASCE, 98(SM4), 361-380, April 1972.

Properly compacted and stabilized fly ash has the requisite properties for use in load-bearing fills or highway subbases. Lower compacted density of fly ash compared to conventional earthfill makes it more advantageous when a fill or embankment must be constructed over soft compressible ground.

72-3 Ish-Shalom, M., and A. Bentur, "Effects of Aluminate and Sulfate Contents in the Hydration and Strength of Portland Cement Pastes and Mortars," Cement and Concrete Research, 2, 653-662 (1972).

This paper describes an evaluation of the effects of tricalcium aluminate and sulfate contents in portland cement on compressive strength, hydration rate, and hydration products. Three cement samples varying in tricalcium aluminate, and one sample varying in sulfate were used. Tests and analyses included compressive strengths, bound water contents, and free lime contents. Interpretations were based on bound water as a measure of quantity of binding material, and free lime to bound water ratio as a measure of chemical constitution and quality.

72-4 Marks, B. D., and T. A. Halliburton, "Acceleration of Lime-Clay Reactions with Salt," J. Soil Mechanics and Foundations Div., ASCE, 98(SM4), 327-339, April 1972.

It was found that sodium chloride accelerates lime-clay reactions to produce a stabilized subgrade soil. Data acquired during the study support a two-stage reaction system. First, lime-clay reactions produce chemical exchanges of calcium for other cations in the soil, which tends to modify the soil without producing new minerals from pozzolanic reactions (modifications). Second, the lime will react further after exchange to produce new cementitious materials with hydrates of silica and aluminum (stabilization). Use of sodium chloride accelerates and enhances lime-clay reactions during both stages of modification and stabilization.

72-5 Meikle, P. G., "Fly Ash and Bottom Ash," Mining Engineering, 24, 41-43, January 1972.

The article discusses the technical developments in ash beneficiation being carried out by various industrial and manufacturing concerns. The areas of discussion where ash was utilized are: partial replacement of cement in concrete products, structural concrete, dams and other mass concrete structures, stabilizers for road bases, parking areas, etc., lightweight aggregate, and fill material for roads and construction sites.

72-6 Sheahan, J. M., and E. J. Steinbade, "Lime Reclaims Unstable Interior Subgrade During Construction," Civil Engineering, 46, 74-75, June 1972.

The article discusses the practice of lime stabilization utilized in rehabilitating a section of the subgrade in a new complex under construction, at low cost, when rains and heavy equipment damaged the section.

73-1 Bensted, J., and S. P. Varma, "The Low-Form of Calcium Sulfoaluminate (Monosulfate)," Cement Technology, pp. 112-116, May/June 1973.

The formation of monosulfate, $3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$, and its derivatives with trivalent titanium, chromium, manganese, and iron replacing aluminum is reported. During the hydration of portland cements, the monosulfate phase is able to contain these other trivalent metals as well as aluminum. These compounds can all undergo solid solution with one another.

73-2 Gutt, W., and M. A. Smith, "Utilization of By-Product Calcium Sulphate," Chemistry and Industry, No. 13, 7 July 1973.

This article considers alternate uses for phosphogypsum, the by-product calcium sulfate generated in phosphate fertilizer manufacture, and fluoroanhydrite, by-product calcium sulfate from hydrofluoric acid production. The differences between by-product calcium sulfate and natural gypsum are discussed, which hinder the direct substitution of the by-product for the natural product. Among the alternatives discussed are: (a) the use of by-product calcium sulfate as a retarder for portland cement, (b) the recovery of sulfuric acid and cement using by-product sulfate as lime source, and (c) the use of by-product sulfate in expansive or prestressed concretes in road construction.

73-3 Jones, D. E., Jr., and W. G. Haltz, "Expansive Soils--The Hidden Disaster," Civil Engineering--ASCE, pp. 49-51, August 1973.

Expansive soils cover 25% of the United States. Each year, the expansive soils, having adverse shrink-swell properties, inflict at least 2.3 billion dollars in damage to houses, buildings, roads, and pipelines. This value is more than double the damage arising from floods, hurricanes, tornadoes, and earthquakes. Of the 2.3 billion dollar damage, highways and streets are estimated to account for more than 1.1 billion dollars.

73-4 Mehta, P. K., "Effect of Lime on Hydration of Pastes Containing Gypsum and Calcium Aluminates or Calcium Sulfoaluminate," J. Am. Ceramic Soc., 616, 315-319 (1973).

Chemical reactions responsible for ettringite formation in expansive cements are reviewed. X-ray diffraction analyses of the hydrated expansive compounds showed that in the presence of $Ca(OH)_2$ and $CaSO_4$, the tricalcium aluminate hydrated very slowly and the monocalcium aluminate quickly, whereas the calcium sulfoaluminate hydrated at a uniform rate during the early hydration period.

73-4 Minnick, L. J., "In Situ Treatment of Roadways," U.S. Patent 3,753,620, assigned to IU Conversion Systems, Inc., August 21, 1973.

A new bituminous coal fly ash is sulfopozzolanically reactive and contains combined sulfate in stated proportions relative to alkaline earth metal oxide content. Load-supporting compositions of this fly ash combined with aggregate, and a method of applying the new fly ash to an existing surface are described.

73-6 Moulton, L. K., R. K. Seals, and D. A. Anderson, "Utilization of Ash From Coal-Burning Power Plants in Highway Construction," Highway Research Board Record, No. 480, pp. 26-39 (1973).

Studies conducted at West Virginia University have shown that the engineering properties of bottom ash are comparable to those of conventional construction materials used in highway construction. Applications included use of bottom ash or fly ash or both in nonstabilized base courses, bituminous surface courses, lightweight structural fill, and underdrain filters. It found that ash materials can be used satisfactorily in these applications providing their unique properties are recognized and appropriate construction techniques are employed. It is shown that these materials do not always fit within the framework of existing materials and construction

specifications and that adherence to these specifications does not always ensure satisfactory performance.

73-7 Radian Corporation, "Evaluation of Lime/Limestone Sludge Disposal Options," Report to U.S. Enviornmental Protection Agency, Contract No. 68-02-0046, Report No. EPA-450/3-74-016, PB 232022, November 1973.

This report presents results of a study of disposal technology for sludges obtained from limes/limestone flue gas desulfurization units at steam-electric power plants. Properties of sludges are reviewed, as well as their environmental hazards, e.g., toxic chemical content. The report concludes that any large degree of commercial utilization of those sludges is unlikely.

73-8 Ramsey, J. P., "Chemical Agent Effectively Stabilizes," Coal Age, pp. 74-75 (1973).

In a project jointly conducted with the Environmental Protection Agency, 14.5 acres of dry slurry lagoons were treated with a soil stabilizing agent named "Coherex," from Witco Chemical's Golden Bear Division. The dry lagoons, approximately 18 ft deep, contained fine reject material analyzing approximately 50% coal, with the balance ash and pyrite. Results, after more than 2-1/2 years of study, show that the stabilizing agent, a combination of selected petroleum oils and resins, is a nontoxic chemical that appears to be compatible with vegetative covers.

73-9 Varma, S. P., and J. Bensted, "Studies of Thaumasite," Silicates Industrials, 3812, 29-32 (1973).

Thaumasite is a heavily hydrated triple compound of calcium metasilicate, calcium sulfate, and calcium carbonate in the ratio 1:1:1. It occurs naturally as a rare mineral in metamorphized rocks which have undergone hydrothermal changes, and as a deterioration product in some concrete specimens. Thaumasite is slowly formed by interaction of $CaSO_4 \cdot 2H_2O$ and $CaCO_3$ in air and water at 1 to 4°C with tricalcium silicate, β-dicalcium silicate, or with lime and silica.

73-10 Wright, P. J., "Lime Slurry Pressure Injection Tames Expansive Clays," Civil Engineering--ASCE, pp. 42-45 (1973).

Shrinking or swelling soils under foundations inflict at least $2.3 billion per year in damages to houses, buildings, roads, and pipelines.

In this article, the author presents a promising and relatively inexpensive solution to many of these unstable soil problems--lime slurry pressure injection (LSPI). In this technique, a lime slurry is pumped into the soil under pressure, forming a network of interconnecting, sheetlike seams. These seams act as moisture barriers, preventing the movement of moisture either into or out of the soil. Since the soil's moisture content is now constant, moisture-induced swelling or shrinkage of soils is eliminated.

74-1 Joshi, R. C., D. M. Duncan, and H. McMaster, "New and Conventional Uses of Fly Ash," Paper presented at ASCE Annual and National Environmental Engineering Convention, Kansas City, Missouri, October 21-25, 1974.

Flue gas desulfurization sludge (a mixture of calcium sulfate, unreacted limestone and fly ash) from the Kansas City Power and Light Company La Cygne Station was evaluated with respect to engineering properties of a highly plastic clay. It was found that addition of 15% of the waste sulfate to the clay increases maximum density and decreases optimum moisture content. In addition, this system had an unconfined compressive strength of 538 psi, compared to 204 psi for a 15% fly ash system and 131 psi for a 5% lime-fly ash system.

APPENDIX B

ATTERBERG LIMIT DATA AND MOISTURE-DENSITY RELATIONSHIPS OF SOIL/SULFATE WASTE SYSTEMS

A. Class I Soils: Plasticity Index NP-10
B. Class II Soils: Plasticity Index 10-25
C. Class III Soils: Plasticity Index > 25, Nonmontmorillonitic
D. Class IV Soils: Plasticity Index > 20, Montmorillonitic

Key:

PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutralization Solids (Pennsylvania)

A. CLASS I SOILS

ATKINS SERIES
FINE-LOAMY, MIXED, ACID, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	25	NP	NP	112	15
6 FGl	26	NP	NP	108	17
9 FGl	27	NP	NP	107	17
12 FGl	28	NP	NP	106	18
6 AMD	28	NP	NP	107	17
9 AMD	29	NP	NP	104	20
12 AMD	30	NP	NP	100	20

CHARLTON SERIES
COARSE-LOAMY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	31	NP	NP	106	16
6 FG1	33	NP	NP	101	20
9 FG1	34	NP	NP	100	21
12 FG1	36	NP	NP	100	21
6 AMD	33	NP	NP	101	20
9 AMD	36	NP	NP	100	22
12 AMD	37	NP	NP	99	23

CONVENT SERIES
COARSE-SILTY, MIXED, NONACID, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	28	NP	NP	102	17
6 PG1	28	NP	NP	99	20
9 PG1	28	NP	NP	98	21
12 PG1	28	NP	NP	98	21
6 PG3	28	NP	NP	99	18
9 PG3	28	NP	NP	98	20
12 PG3	30	NP	NP	98	19

COXVILLE SERIES
CLAYEY, KAOLINITIC, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	23	14	9	116	13
6 PG2	23	15	8	117	14
9 PG2	24	15	9	115	13
12 PG2	25	16	9	116	14

DELRAY SERIES
LOAMY, MIXED, NONCALCAREOUS, HYPERTHERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	NP	NP	NP	102	12
6 PG1	NP	NP	NP	102	13
9 PG1	NP	NP	NP	100	11
12 PG1	NP	NP	NP	99	13

HAZELTON SERIES
LOAMY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	20	NP	NP	112	15
6 FGl	22	NP	NP	107	17
9 FGl	24	NP	NP	106	16
12 FGl	25	NP	NP	103	19
6 AMD	24	NP	NP	108	16
9 AMD	31	NP	NP	104	20
12 AMD	27	NP	NP	101	20

KENDRICK SERIES
LOAMY, SILICEOUS, HYPERTHERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	20	NP	NP	121	11
6 PG1	19	NP	NP	121	16
9 PG1	19	NP	NP	119	13
12 PG1	20	NP	NP	119	14

MANOR SERIES
COARSE-LOAMY, MICACEOUS, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	35	NP	NP	113	16
6 FGl	36	NP	NP	105	19
9 FGl	37	NP	NP	105	20
12 FGl	39	NP	NP	100	22
6 AMD	38	NP	NP	106	19
9 AMD	40	NP	NP	109	18
12 AMD	42	NP	NP	105	18

NORFOLK SERIES
FINE-LOAMY, SILICEOUS, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	16	11	5	126	10
6 PG1	15	NP	NP	125	11
9 PG1	17	NP	NP	124	10
12 PG1	17	NP	NP	122	12
6 PG2	16	11	5	124	11
9 PG2	16	13	3	125	11
12 PG2	17	14	3	126	10

PRENTISS SERIES
COARSE-LOAMY, SILICEOUS, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	20	18	2	115	12
6 PG2	20	NP	NP	113	12
9 PG2	21	NP	NP	115	14
12 PG2	21	NP	NP	111	15
6 PG3	20	NP	NP	105	13
9 PG3	20	NP	NP	103	13
12 PG3	22	NP	NP	101	14

WAGRAM SERIES
LOAMY, SILICEOUS, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	NP	NP	NP	124	8
6 PG2	NP	NP	NP	121	9
9 PG2	NP	NP	NP	119	10
12 PG2	NP	NP	NP	118	11

B. CLASS II SOILS

COMMERCE SERIES
FINE-SILTY, MIXED NONACID, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	36	22	14	105	18
6 PG1	36	21	15	101	20
9 PG1	36	22	14	101	22
12 PG1	36	24	13	100	22
6 PG3	36	23	13	103	20
9 PG3	35	24	11	100	20
12 PG3	35	24	11	101	20

EXUM SERIES
FINE-SILTY, SILICEOUS, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	34	17	17	109	17
6 PG2	30	15	15	109	18
9 PG2	31	16	15	109	18
12 PG2	30	16	14	109	18

MAHONING SERIES
FINE, ILLITIC, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	42	22	20	104	20
6 PG3	37	20	17	101	24
9 PG3	38	22	16	102	21
12 PG3	39	23	16	102	22
6 FG1	43	22	21	99	23
9 FG1	43	23	20	99	23
12 FG1	45	24	21	99	24
6 AMD	45	27	18	101	22
9 AMD	46	29	17	97	25
12 AMD	47	29	18	96	25

MEMPHIS SERIES
FINE-SILITY, MIXED, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	44	22	22	100	20
6 PG1	42	22	20	100	23
9 PG1	41	22	19	99	24
12 PG1	40	22	18	99	24
6 PG3	41	23	18	101	19
9 PG3	43	22	21	101	21
12 PG3	44	22	22	104	23

MIAMI SERIES
FINE-LOAMY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	34	18	16	108	17
6 PG2	36	17	19	107	19
9 PG2	36	18	18	106	18
12 PG2	36	18	18	105	20
6 FG1	39	18	21	104	20
9 FG1	37	19	18	101	20
12 FG1	37	21	16	101	20
6 AMD	36	22	14	103	22
9 AMD	37	22	15	101	21
12 AMD	38	23	15	100	23

SASSAFRASS SERIES
FINE-LOAMY, SILICEOUS, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	28	14	14	117	13
6 FGl	29	16	13	115	14
9 FGl	30	18	12	113	14
12 FGl	32	19	13	112	15
6 AMD	31	16	15	112	16
9 AMD	31	18	13	107	16
12 AMD	32	20	12	106	18

SHELBY SERIES
FINE-LOAMY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	47	23	24	102	20
6 FG2	43	20	23	104	19
9 FG2	42	20	22	105	19
12 FG2	40	20	20	106	18
6 AMD	49	27	22	100	21
9 AMD	48	28	20	102	20
12 AMD	49	29	20	99	21

TAMA SERIES
FINE-SILITY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	50	28	22	98	23
6 PG3	48	25	23	98	23
9 PG3	48	26	22	98	24
12 PG3	48	26	22	97	22
6 FG1	53	24	29	93	25
9 FG1	57	25	32	92	26
12 FG1	52	27	25	92	25
6 AMD	52	29	23	93	26
9 AMD	51	31	20	91	27
12 AMD	54	32	22	90	28

WHARTON SERIES
CLAYEY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	47	24	23	99	24
6 FGl	49	27	22	92	24
9 FGl	50	29	21	94	26
12 FGl	52	29	23	94	27
6 AMD	52	27	25	95	27
9 AMD	51	29	22	93	28
12 AMD	52	31	21	90	27

C. CLASS III SOILS

CHOBEE SERIES
FINE-LOAMY, MIXED, NONCALCAREOUS, HYPERTHERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	49	18	31	105	20
6 PG1	47	19	28	105	20
9 PG1	46	19	27	104	20
12 PG1	47	20	27	103	21

CRAVEN SERIES
CLAYEY, MIXED, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	62	25	37	94	26
6 PG2	54	23	31	98	28
9 PG2	52	23	29	93	25
12 PG2	52	20	32	93	25

HARTWELL SERIES
FINE, MIXED, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	53	24	29	100	21
6 FG2	48	21	27	100	23
9 FG2	45	20	25	107	15
12 FG2	45	21	24	107	15

HIGGINSVILLE SERIES
FINE-SILTY, MIXED, MESIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	65	28	37	94	25
6 FG1	66	26	40	89	27
9 FG1	66	27	39	89	29
12 FG1	66	30	36	89	28
6 FG2	62	24	38	94	23
9 FG2	60	24	36	96	24
12 FG2	56	23	33	94	23

KATY SERIES
FINE-LOAMY, SILICEOUS, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	63	18	45	100	21
6 PG3	52	17	35	101	22
9 PG3	51	18	33	103	19
12 PG3	51	18	33	100	20

UPSHUR SERIES
FINE, MIXED, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	54	28	26	98	24
6 FGl	57	29	28	101	22
9 FGl	58	29	29	100	24
12 FGl	58	31	27	99	22
6 AMD	58	31	27	99	24
9 AMD	59	32	27	99	23
12 AMD	60	33	27	97	23

D. CLASS IV SOILS

FELLOWSHIP SERIES
FINE, MONTMORILLONITIC, HYPERTHERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	51	28	23	87	30
6 PG1	50	28	22	87	31
9 PG1	50	26	24	87	30
12 PG1	47	26	21	89	30

LAKE CHARLES SERIES
FINE, MONTMORILLONITIC, THERMIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	60	27	33	97	25
6 PG3	59	25	34	95	21
9 PG3	58	24	34	96	23
12 PG3	54	23	31	94	21

SHARKEY SERIES
VERY FINE, MONTMORILLONITIC, NONACID, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	91	30	61	87	26
6 PG1	89	32	57	88	30
9 PG1	83	30	53	88	31
12 PG1	84	31	53	89	30
6 PG3	78	32	46	86	28
9 PG3	81	34	47	86	31
12 PG3	80	33	47	86	34

SHARPSBURG SERIES
FINE, MONTMORILLONITIC, MESIC

Sulfate Waste (%)	System Characteristics: Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	60	27	33	95	23
6 PG2	55	27	28	93	26
9 PG2	54	27	27	93	26
12 PG2	52	27	25	92	27
6 PG3	54	27	27	95	26
9 PG3	54	28	26	95	24
12 PG3	51	27	24	94	25
6 FG1	62	26	36	91	27
9 FG1	61	27	34	90	28
12 FG1	59	26	33	89	28
6 FG2	54	27	27	98	24
9 FG2	52	23	29	101	20
12 FG2	52	26	26	99	21
6 AMD	56	27	29	91	27
9 AMD	56	28	28	89	28
12 AMD	58	28	30	87	30

SUMMIT SERIES
FINE, MONTMORILLONITIC, THERMIC

Sulfate Waste (%)	System Characteristics				
	Liquid Limit (% H_2O)	Plastic Limit (% H_2O)	Plasticity Index (Δ % H_2O)	Maximum Density (lb/cu ft)	Optimum Moisture (% H_2O)
0	69	30	39	96	26
6 FG2	60	26	34	95	24
9 FG2	57	25	32	95	23
12 FG2	56	24	32	96	20

APPENDIX C

UNCONFINED COMPRESSIVE STRENGTH RAW DATA

A. Class I Soils, Plasticity Index NP to 10
B. Class II Soils, Plasticity Index 10 to 25
C. Class III Soils, Plasticity Index > 25, Nonmontmorillonitic
C. Class IV Soils, Plasticity Index > 20, Montmorillonitic

Key:

PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutralization Solids (Pennsylvania)

A. Class I Soils

ATKINS SERIES
FINE-LOAMY, MIXED, ACID, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	28, 32 (14, 14)	23, 33 (14, 14)	34, 32 (14, 14)	31, 37, 18, 23 (14, 14, 15, 14)
6% FGl	25 (16)	30 (16)	30 (16)	27, 18 (16, 16)
9% FGl	27 (16)	31 (15)	31 (16)	21 (16)
12% FGl	28 (18)	33 (17)	32 (16)	15, 23 (18, 18)
6% AMD	30 (16)	27 (16)	30 (16)	31, 33 (17, 16)
9% AMD	25 (19)	27 (19)	29 (19)	24, 31 (20, 19)
12% AMD	35 (19)	13 (19)	37 (19)	29, 32 (19, 19)

CHARLTON SERIES
COARSE-LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	27 (15)	30 (15)	28 (15)	28, 21 (15, 16)
2% Lime	27 (14)	22 (15)	-	-
6% FGl 2% Lime	44 (17)	35 (18)	38 (17)	31, 33 (18, 18)
12% FGl 2% Lime	42 (21)	48 (19)	45 (18)	41, 47 (18, 18)
6% AMD	26 (19)	25 (19)	29 (19)	25, 25 (19, 20)
9% AMD	24 (20)	32 (20)	26 (24)	29, 21 (21, 23)
12% AMD	27 (21)	28 (21)	34 (21)	20, 28 (22, 20)

CONVENT SERIES
COARSE-SILTY, MIXED, NONACID, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	19 (18)	14 (18)	21 (18)	21, 19 (18, 18)
6% Lime	-	22 (15)	-	36, 33[a/] (16, 15)
6% Lime	-	24, 28, 25 (17, 17, 17)	-	41, 46, 44 (17, 17, 17)
6% PG1 6% Lime	-	35 (17)	-	97, 93, 101[a/] (18, 17, 17)
6% PG1 6% Lime	28, 26, 31 (18, 18, 18)	64, 53, 64 (18, 18, 18)	-	140, 138, 154 (18, 18, 18)
12% PG1 6% Lime	-	42 (19)	-	107, 105, 122[a/] (19, 19, 18)
12% PG1 6% Lime	28, 27 (19, 19)	59, 62, 62 (19, 19, 19)	-	140, 129, 122 (18, 19, 18)
6% PG3	19 (18)	19 (18)	21 (19)	20, 19 (19, 19)
9% PG3	18 (20)	19 (20)	17 (21)	19, 17 (21, 21)
12% PG3	17 (20)	18 (20)	17 (20)	17, 17 (19, 20)

a/ 32 days.

COXVILLE SERIES
CLAYEY, KAOLINITIC, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	40 (13)	-	40 (12)	39, 44 (12, 12)
6% Lime	-	48, 44, 44 (14, 14, 14)	-	58, 51, 65 (14, 14, 13)
6% PG2	38 (13)	34 (14)	2525 ((13)	35, 31 (13, 44)
9% PG2	33 (13)	36 (13)	35 (13)	31, 33 (13, 13)
12% PG2	29 (14)	30 (14)	31. (14)	33, 25 (14, 15)
6% PG2 6% Lime	67, 57, 64 (15, 15, 15)	84, 81, 93 (15, 15, 15)	-	44, 33, 153 (20, 20, 15)
12% PG2 6% Lime	64, 58, 53 (16, 16, 16)	114, 105, 110 (17, 17, 16)	-	43, 50, 59 (24, 23, 21)
2% PG2 2% Lime 4% Fly Ash	-	123, 131, 130 (15, 15, 15)	-	161, 93, 90 (14, 17, 17)
2% PG2 6% Lime 4% Fly Ash	-	153, 155, 155 (15, 14, 15)	-	44, 121, 60 (17, 15, 19)
4% PG2 2% Lime 8% Fly Ash	-	128, 118, 122 (15, 15, 15)	-	169, 82, 207 (15, 18, 15)
4% PG2 6% Lime 8% Fly Ash	-	192, 188, 216 (15, 15, 15)	-	246, 250, 236 (15, 15, 15)

DELRAY SERIES
LOAMY, MIXED, NONCALCAREOUS, HYPERTHERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	3, 3, 3 (15, 15, 15)	-	3, 4, 3 (15, 15, 15)
6% Cement	-	16 (10)	-	30, 25, 20[a/] (9, 9, 10)
6% PG1	-	3, 3 (12, 12)	-	2 (12)
12% PG1	-	3, 3, 3 (15, 15, 15)	-	3, 3, 3 (15, 15, 15)
6% PG1 6% Cement	-	-	-	8, 9[a/] (13, 22)
12% PG1 6% Cement	-	6 (14)	-	12, 13, 13[a/] (14, 14, 13)

a/ 31 days.

HAZELTON SERIES
LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	19, 23 (14, 14)	21, 21 (14, 14)	19, 19 (15, 15)	17, 16, 25, 23 (15, 15, 15, 14)
6% Lime	-	42, 32, 31 (14, 14, 14)	-	42, 36 (13, 14)
6% Kiln Dust	-	31, 28, 31 (13, 13, 13)	-	33, 35, 34 (13, 13, 13)
6% FGl	23 (16)	23 (16)	24 (16)	20, 10 (16, 20)
9% FGl	23 (14)	25 (18)	24 (15)	26 (15)
12% FGl	27 (17)	14 (20)	19 (17)	23, 18 (17, 18)
6% FGl 2% Lime	60, 48, 63 (16, 16, 16)	60, 49 (15, 16)	-	53, 64 (16, 15)
12% FGl 2% Lime	55, 49, 59 (17, 18, 17)	75, 75, 63 (16, 18, 17)	-	75, 68, 65 (18, 17, 18)
6% AMD	27 (16)	24 (16)	20 (15)	23, 14 (16, 18)
9% AMD	23 (20)	22 (19)	17 (21)	25, 18 (19, 20)
12% AMD	28 (29)	18 (20)	21 (19)	18 (20)
6% AMD 2% Lime	23, 22, 27 (15, 15, 14)	22, 22, 20 (15, 15, 15)	-	8 (24)

HAZELTON (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
12% AMD 2% Lime	24, 24, 25 (18, 19, 19)	24, 26, 23 (18, 19, 19)	-	16, 25, 14 (20, 17, 21)
6% AMD 4% Kiln Dust	-	38 (13)	-	29, 28 (14, 15)
6% AMD 8% Kiln Dust	-	65, 59, 51 (13, 12, 14)	-	55, 66, 64 (12, 14, 14)
12% AMD 4% Kiln Dust	-	42, 41 (16, 17)	-	39, 33, 34 (15, 18, 18)
12% AMD 8% Kiln Dust	-	44, 48, 62 (16, 15, 15)	-	48, 41, 50 (16, 17, 15)

KENDRICK SERIES
LOAMY, SILICEOUS, HYPERTHERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	15, 16, 15 (10, 10, 10)	-	17, 19 (10, 10)
6% Cement	-	-	-	290, 224 (8, 8)
6% PG1	-	18, 20, 22 (11, 11, 11)	-	23, 24, 22 (11, 11, 11)
12% PG1	-	15 (13)	-	14, 13, 17 (13, 13, 13)
6% PG1 6% Cement	-	-	-	361, 381 (10, 10)
12% PG1 6% Cement	-	85 (11)	-	145, 345 (11, 18)

MANOR SERIES
COARSE-LOAMY, MICACEOUS, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	23 (15)	20 (15)	22, 20 (16, 15)
2% Lime	23 (14)	30 (14)	24 (18)	26 (14)
6% Lime	-	25, 43, 43 (16, 14, 14)	-	54, 51, 38 (15, 14, 15)
6% Kiln Dust	-	57, 65, 57 (15, 14, 14)	-	55, 78, 71 (15, 14, 14)
6% FGl 2% Lime	43 (17)	69 (17)	56 (18)	48, 46 (17, 18)
6% FGl 2% Lime	40, 38, 37 (17, 17, 17)	44, 51, 45 (18, 17, 17)	-	46, 52, 54 (17, 17, 17)
12% FGl 2% Lime	46 (19)	72 (19)	73 (19)	42, 40 (21, 20)
12% FGl 2% Lime	42, 43, 45 (19, 18, 19)	56, 53, 50 (19, 19, 19)	-	47, 54, 59 (20, 19, 18)
6% AMD	20 (18)	24 (19)	18 δ (19)	23, 26 (18, 17)
9% AMD	24 (16)	33 (17)	28 (17)	32, 32 (17, 16)
12% AMD	27 (16)	-	-	33, 32 (16, 16)
6% AMD 2% Lime	26, 27, 29 (17, 18, 17)	26, 27, 29 (17, 17, 17)	-	27, 28, 26 (17, 17, 17)

MANOR SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
12% AMD 2% Lime	22, 24 (16, 17)	-	-	-
6% AMD 4% Kiln Dust	-	40, 48 (17, 16)	-	39, 47, 45 (16, 16, 15)
6% AMD 8% Kiln Dust	-	72, 59, 57 (16, 16, 15)	-	44, 57, 63 (18, 15, 15)
12% AMD 4% Kiln Dust	-	53, 46, 38 (16, 16, 16)	-	43, 44, 42 (16, 17, 17)
12% AMD 8% Kiln Dust	-	59, 54 (17, 17)	-	67, 66, 68 (17, 17, 17)

NORFOLK SERIES
FINE-LOAMY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	22 (10)	23 (10)	22 (9)	26, 26 (9, 9)
6% Lime	-	47, 46, 53 (9, 9, 9)	-	87, 79, 80 (9, 9, 9)
6% Cement	-	276 (8)	-	397, 374, 314 (8, 8, 8)
6% PG1 6% Lime	39, 49 (10, 11)	75, 69 (10, 10)	-	105, 18, 30 (10, 23, 14)
12% PG1 6% Lime	41, 36 (11, 11)	54, 55 (10, 9)	-	82, 82, 27 (11, 11, 14)
6% PG1 6% Cement	-	243 (9)	-	348, 125, 72 (9, 11, 13)
6% PG2	20 (11)	20 (11)	18 (11)	21, 14 (11, 12)
9% PG2	18 (11)	19 (11)	22 (11)	22, 21 (11, 11)
12% PG2	23 (10)	24 (11)	24 (11)	20, 23 (11, 11)

PRENTISS SERIES
COARSE-LOAMY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	25 (11)	26 (11)	28 (11)	21, 26 (12, 11)
None	32, 29 (11, 11)	30, 27, 33 (11, 11, 11)	29, 26, 28 (11, 11, 11)	33, 32, 24 (12, 11, 12)
6% Lime	-	49, 46, 49 (10, 11, 11)	-	56, 52, 54 (11, 11, 10)
6% PG2	26 (12)	30 (12)	29 (12)	31 (12)
9% PG2	25 (13)	26 (13)	28 (13)	31, 25 (13, 13)
12% PG2	24 (14)	23 (14)	27 (14)	26 (14)
6% PG3	31, 29, 31 (14, 14, 14)	30, 30, 33 (14, 14, 13)	28, 29, 29 (14, 14, 14)	30, 30, 28 (14, 14, 14)
9% PG3	31, 31, 29 (13, 13, 13)	34, 29, 29 (13, 13, 13)	28, 29 (13, 13)	28, 29, 29 (15, 13, 13)
12% PG3	28, 32, 29 (15, 14, 14)	27, 30, 30 (14, 14, 14)	27, 33 (14, 14)	29, 26 (14, 15)
6% PG3 6% Lime	41, 51, 59 (13, 13, 12)	96, 82, 72 (12, 13, 13)	-	148, 69, 81 (16, 16, 15)
12% PG3 6% Lime	61, 54, 53 (15, 22, 15)	93, 84, 78 (12, 15, 15)	-	72, 69, 53 (17, 18, 20)
2% PG3 2% Lime 4% Fly Ash	-	143, 133, 119 (12, 11, 11)	-	141, 138, 151 (12, 12, 12)

PRENTISS (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
2% PG3 6% Lime 4% Fly Ash	-	153, 125, 154 (11, 11, 11)	-	135, 184, 195 (12, 11, 11)
4% PG3 2% Lime 8% Fly Ash	-	105, 102, 109 (12, 12, 12)	-	137, 100, 130 (12, 15, 12)
4% PG3 6% Lime 8% Fly Ash	-	53, 80, 91 (13, 12, 12)	-	137, 67, 129 (11, 16, 11)

WAGRAM SERIES
LOAMY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	6 (7)	5 (8)	7 (8)	-
6% PG2	8 (9)	9 (9)	9 (9)	8 (9)
9% PG2	10 (10)	11 (10)	9 (10)	12, 11 (10, 10)
12% PG2	9 (12)	12 (11)	12 (11)	11, 11 (11, 11)

B. Class II Soils

COMMERCE SERIES
FINE-SILTY, MIXED, NONACID, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	35, 34, 37 (18, 18, 18)	37, 35, 34 (18, 18, 18)	32, 32, 31 (18, 18, 18)	36, 38, 39 (18, 18, 18)
6% Lime	-	43 (16)	-	53, 50, 50 (15, 16, 15)
6% Lime	-	57, 48, 47 (17, 17, 17)	-	61, 52, 53 (17, 17, 17)
6% PG1 6% Lime	-	65 (17)	-	128, 139, 65 (17, 17, 24)
6% PG1 6% Lime	34, 37, 44 (18, 18, 18)	64, 55, 66 (19, 18, 18)	-	124, 116, 83 (18, 20, 18)
12% PG1 6% Lime	-	64 (19)	-	130, 128, 127 (19, 19, 18)
12% PG1 6% Lime	45, 43, 43 (20, 20, 20)	74, 72, 65 (20, 20, 19)	-	119, 125, 89 (19, 21, 22)
2% PG1 2% Lime 4% Fly Ash	-	72, 74, 76 (18, 18, 18)	-	94, 90, 96 (18, 18, 18)
2% PG1 6% Lime 4% Fly Ash	-	92, 73, 87 (17, 17, 17)	-	145, 132, 119 (17, 17, 17)
4% PG1 2% Lime 8% Fly Ash	-	66, 70, 62 (19, 18, 18)	-	88, 101, 98 (19, 19, 19)

COMMERCE SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
4% PG1 6% Lime 8% Fly Ash	-	77, 81, 86 (19, 18, 18)	-	156, 165 (19, 18)
6% PG3	43, 37, 33 (18, 19, 19)	41, 43, 46 (19, 18, 19)	36, 40, 41 (19, 19, 19)	43, 39, 46 (19, 19, 18)
9% PG3	40, 45, 41 (20, 20, 20)	39, 46, 40 (19, 20, 20	42, 32, 39 (19, 19, 19)	47, 29, 46 (19, 19, 19)
12% PG3	38, 37, 41 (20, 20, 20)	37, 41, 35 (20, 20, 20)	38, 34, 41 (20, 20, 20)	38, 40, 39 (19, 20, 20)

EXUM SERIES
FINE-SILTY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	33 (16)	34 (16)	30 30 (17)	32, 33 (16, 16)
6% Lime	-	65, 70, 60 (18, 18, 18)	-	96, 123, 110 (18, 17, 17)
6% PG2	26 (16)	29 (17)	29 (18)	29, 28 (17, 17)
9% PG2	28 (18)	30 (17)	26 (18)	31, 29 (17, 17)
12% PG2	28 (18)	30 (18)	26 (18)	24, 18 (18, 19)
6% PG2 6% Lime	53, 67, 57 (19, 20, 20)	146, 115, 171 (20, 20, 20)	-	335, 330 (20, 20)
12% PG2 6% Lime	46, 58, 52 (23, 23, 23)	133, 131, 114 (23, 22, 23)	-	260, 255, 44 (23, 22, 33)

MAHONING SERIES
FINE, ILLITIC, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
Control	47, 33, 46 (20, 20, 20)	47, 50 (19, 19)	44, 44, 40 (21, 20, 20)	37, 45, 36 (19, 19, 20)
Control	46, 45 (19, 18)	45, 37 (24, 18)	44, 28 (20, 19)	29, 41, 18 (21, 19, 23)
6% Lime	-	53, 43, 42 (19, 18, 18)	-	41, 56, 54 (19, 18, 18)
6% Kiln Dust	-	69, 77, 64 (18, 18, 18)	-	51, 88 (18, 18)
6% PG3	27, 23, 24 (22, 24, 24)	34, 30 (22, 23)	29, 33 (23, 22)	27, 30, 27 (24, 24, 24)
9% PG3	44, 41, 44 (20, 19, 21)	42, 41 (21, 20)	41, 42, 43 (21, 21, 21)	45, 47, 45 (21, 21, 21)
12% PG3	36, 46, 40 (21, 21, 21)	32, 30, 33 (14, 14, 14)	38, 38, 39 (22, 21, 21)	46, 50, 49 (21, 21, 21)
6% PG3 6% Lime	65, 59, 52 (18, 18, 18)	70, 70 (17, 17)	-	24, 46, 85 (26, 19, 18)
12% PG3 6% Lime	63, 57, 49 (20, 20, 20)	63, 75, 78 (16, 20, 20)	-	94, 85, 96 (20, 20, 20)
2% PG3 2% Lime 4% Fly Ash	-	100, 79, 107 (18, 19, 18)	-	84, 72, 88 (18, 18, 18)
2% PG3 6% Lime 4% Fly Ash	-	109, 100, 110 (19, 18, 19)	-	102, 114, 110 (19, 19, 20)
4% PG3 2% Lime 8% Fly Ash	-	76, 75, 115 (18, 19, 19)	- -	84, 72, 88 (19, 19, 19)

MAHONING (Continued)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
4% PG3 6% Lime 8% Fly Ash	-	91, 102, 75 (18, 18, 18)	-	94, 100, 114 (23, 19, 18)
6% FG1	38 (20)	39 (20)	31 (22)	34 (21)
6% FG1 2% Lime	48, 49, 51 (21, 21, 21)	50, 59, 63 (20, 21, 20)	-	41, 56, 54 (20, 20, 21)
9% FG1 2% Lime	51 (20)	73 (20)	64 (19)	72 (20)
12% FG1 2% Lime	71 (20)	59 (20)	65 (21)	53 (20)
12% FG1 2% Lime	61, 60, 62 (23, 23, 24)	59, 66, 58 (23, 23, 24)	-	41, 36, 59 (24, 25, 23)
6% AMD	46 (20	46 (21)	44 (21)	36, 40 (21, 21)
9% AMD	35 (23)	40 (23)	35 (23)	33, 24 (24, 25)
12% AMD	42 (23)	38 (23)	39 (24)	36, 38 (24, 23)
6% AMD 2% Lime	35, 32, 43 (19, 19, 19)	36, 39, 35 (20, 19, 19)	-	24, 40 (18, 19)
12% AMD 2% Lime	36, 30, 36 (21, 22, 21)	34, 37, 29 (22, 22, 21)	-	25, 35, 38 (23, 21, 22)
6% AMD 4% Kiln Dust	-	67, 61 (19, 19)	-	50, 52, 51 (19, 18, 19)

MAHONING SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
6% AMD 8% Kiln Dust	-	71, 73 (19, 18)	-	58, 49, 69 (19, 21, 18)
12% AMD 4% Kiln Dust	-	47, 42, 38 (21, 21, 20)	-	18, 39, 41 (28, 21, 21)
12% AMD 8% Kiln Dust	-	55, 65, 78 (19, 20, 20)	-	62, 64, 36 (19, 20, 24)
Freeze-Thaw 6% PG3	-	13, 8, 17 (27, 26, 25)	-	-
Freeze-Thaw 6% PG3 6% Lime	-	30, 28, 19 (33, 33, 36)	-	-

MEMPHIS SERIES
FINE-SILTY, MIXED, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	49 (19)	44 (20)	54 (19)	41, 49 (20, 19)
6% Lime	-	-	-	99, 92, 104 (18, 20, 17)
6% PG1 6% Lime	-	165 (20)	-	216, 161, 232 (20, 21, 19)
12% PG1 6% Lime		167 (21)		154, 226, 211 (23, 21, 21)
6% PG3	41 (18)	44 (22)	44 (19)	39, 39 (19, 19)
9% PG3	42 (19)	34 (21)	36 (20)	38, 44 (21, 21)
12% PG3	35 (21)	34 (22)	35 (21)	35, 32 (22, 22)

MIAMI SERIES
FINE-LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	50, 40 (17, 16)	51, 46 (16, 14)	40, 38 (16, 16)	41, 47, 46 (17, 17, 17)
2% Lime	34 (16)	35 (16)	-	32 (15)
6% Lime	-	68, 63, 49 (15, 14, 14)	-	69, 72, 73 (14, 14, 14)
6% PG2	39 (20)	36 (18)	34 (22)	33, 37 (19, 19)
9% PG2	39 (19)	40 (19)	39 (21)	38, 43 (18, 18)
12% PG2	31 (21)	32 (21)	39 (22)	37, 27 (20, 20)
6% FG1 2% Lime	-	52 (19)	57 (18)	-
6% FG1 2% Lime	49, 49, 48 (18, 18, 19)	56, 56, 64 (18, 18, 18)	-	34, 50 (21, 20)
12% FG1 2% Lime	66 (18)	68 (18)	47 (20)	57 (20)
12% FG1 2% Lime	53, 50, 56 (20, 21, 21)	57, 60, 57 (20, 21, 21)	-	37, 54, 60 (21, 20, 20)
6% AMD	34 (22)	33 (16)	37 (22)	36 (22)
9% AMD	36 (21)	46 (18)	41 (19)	42 (21)
12% AMD	35 (22)	40 (22)	39 (22)	45 (22)

SASSAFRAS SERIES
FINE-LOAMY, SILICEOUS, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	33, 33 (13, 12)	26, 34 (13, 12)	31, 14 (1(12, 14)	28, 15, 22 (12, 14, 14)
6% Lime	-	41, 59, 64 (23, 12, 11)	-	69, 62, 73 (11, 11, 11)
6% FGl	32 (13)	32 (13)	32 (13)	26, 23 (14, 14)
9% FGl	37 (13)	28 (13)	31 (16)	21, 16 (14, 15)
12% FGl	39 (15)	-	35 (15)	-
6% FGl 2% Lime	48, 61, 51 (12, 13, 13)	64, 79, 70 (13, 13, 13)	-	59, 64, 79 (12, 13, 12)
12% FGl 2% Lime	45, 42, 50 (13, 13, 13)	66, 65, 65 (13, 13, 13)	-	67, 64 (13, 13)
6% AMD	30 (16)	32 (16)	36 (16)	28, 34 (16, 15)
9% AMD	41 (15)	47 (15)	24 (17)	50 (15)
12% AMD	24 (18)	21 (19)	27 (18)	27, 43 (17, 17)
6% AMD 2% Lime	35, 33, 31 (14, 15, 15)	14, 32, 33 (14, 15, 15)	-	32, 29 (14, 15)
12% AMD 2% Lime	29, 33 (16, 16)	29, 20 (17, 17)	-	28, 23 (16, 16)

SHELBY SERIES
FINE-LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	36, 48 (21, 18)	34, 48 (21, 19)	28, 43, 43, 45 (21, 19, 19, 20)	43, 38, 51, 36, 28 (21, 20, 19, 19, 21)
6% Lime	-	37, 48, 49 (20, 19, 18)	-	41, 70, 53 (20, 18, 19)
6% Kiln Dust	-	77, 68, 68 (17, 18, 18)	-	85, 61, 65 (17, 18, 18)
6% FG2	49 (17)	48 (17)	42, 55, 55 (17, 17, 17)	50, 26, 45 (17, 19, 17)
9% FG2	46 (16)	46, 41, 49 (17, 17, 17)	21, 44, 44 (19, 17, 17)	40, 35, 48 (17, 17, 16)
12% FG2	40 (16)	50, 38, 40 (16, 16, 16)	40, 43, 44 (17, 16, 16)	50, 42, 43 (16, 17, 16)
6% FG2 2% Lime	51, 39 (17, 17)	60, 62, 74 (17, 17, 17)	-	57, 74, 72 (21, 17, 17)
12% FG2 2% Lime	40, 40, 35 (15, 16, 15)	61, 43 (16, 15)	-	52, 38, 51 (16, 16, 16)
6% FG2 4% Kiln Dust	-	57, 84, 46 (16, 16, 19)	-	39, 48, 69 (25, 25, 18)
6% FG2 8% Kiln Dust	-	104, 91, 81 (15, 16, 16)	-	93, 109 (16, 15)
12% FG2 4% Kiln Dust	-	79, 86, 94 (16, 16, 16)	-	89, 74, 84 (16, 16, 16)
12% FG2 8% Kiln Dust	-	90, 90, 96 (15, 15, 16)	-	101, 97, 115 (15, 15, 15)

SHELBY SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
6% AMD	54 (19)	45 (20)	46 (20)	53, 48 (20, 21)
9% AMD	52 (20)	44 (20)	46 (20)	44, 49 (20, 21)
12% AMD	42 (21)	39 (21)	39 (20)	44, 43 (21, 21)
6% AMD 2% Lime	38, 32, 40 (19, 19, 19)	40, 39, 38 (19, 19, 19)	-	35, 34, 40 (18, 18, 17)
12% AMD 2% Lime	36, 30, 36 (18, 18, 19)	29, 37, 27 (18, 18, 19)	-	29, 24, 28 (19, 18, 18)

TAMA SERIES
FINE-SILTY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	43, 46, 50, 46 (22, 22, 22, 20)	51, 51, 55, 47 (22, 22, 21, 20)	45, 49, 45, 49 (22, 22, 22, 20)	48, 46, 45, 44, 53 (22, 22, 22, 20, 20)
2% Lime	31 (21)	-	35 (21)	29 (23)
6% Lime	-	46, 57, 55 (20, 20, 20)	-	70, 69, 66 (20, 20, 19)
6% PG3	57, 48, 53 (21, 21, 21)	47, 50, 57 (21, 21, 21)	34, 52, 50 (21, 21, 21)	49, 37, 50 (21, 21, 21)
9% PG3	42, 49, 42 (23, 23, 23)	46, 41, 46 (23, 24, 24)	46, 42, 43 (23, 23, 23)	46, 43, 44 (23, 23, 23)
12% PG3	45, 38, 40 (23, 23, 23)	46, 44, 47 (23, 23, 24)	41 (23)	45, 42, 42 (23, 23, 23)
6% PG3 6% Lime	52, 67, 65 (21, 21, 21)	116, 106, 123 (19, 18, 20)	-	64, 86, 69 (27, 24, 24)
12% PG3 6% Lime	48, 61, 56 (23, 23, 22)	80, 113, 87 (22, 22, 22)	-	114, 97, 106 (22, 22, 23)
6% FG1 2% Lime	45, 46, 49, 46 (22, 21, 22, 23)	41, 44, 36, 42 (22, 22, 23, 22)	47 (23)	46, 44, 36, 37 (21, 21, 24, 23)
12% FG1 2% Lime	44, 41, 50, 44 (23, 26, 23, 21)	43, 41, 45, 44 (24, 23, 23, 22)	-	49, 43, 50, 42 (22, 24, 22, 22)
6% AMD	47 (23)	51 (22)	55 (23)	28, 37 (40, 23)
9% AMD	46 (24)	44 (23)	45 (22)	45, 40 (22, 23)
12% AMD	38 (24)	41 (23)	48 (24)	50, 41 (23, 23)

TAMA SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
6% AMD 2% Lime	29, 39, 38 (25, 24, 25)	30, 43, 57 (25, 25, 25)	-	37, 29, 36 (25, 25, 25)
12% AMD 2% Lime	36, 43, 44 (26, 26, 27)	30, 37, 35 (28, 26, 26)	-	38, 43, 39 (26, 25, 25)
Freeze-Thaw 6% PG3	-	5, 5, 6 (32, 33, 31)	-	-
Freeze-Thaw 6% PG3 6% Lime	-	36, 40, 48 (45, 46, 47)	-	-

WHARTON SERIES
CLAYEY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	31 (23)	34 (23)	36 (24)	29 (24)
2% Lime	54 (22)	42 (22)	36 (22)	47 (21)
6% Lime	-	39, 40, 41 (23, 22, 22)	-	44, 50, 46 (21, 19, 20)
6% Kiln Dust	-	60, 62, 69 (20, 20, 20)	-	55, 57, 47 (20, 20, 20)
6% FGl 2% Lime	54, 56, 61, 58 (22, 22, 22, 21)	26, 55, 65, 57 (24, 22, 22, 21)	66 (21)	56, 57, 59, 46 (22, 21, 22, 21)
12% FGl 2% Lime	49, 57, 41, 65 (24, 24, 24, 22)	56, 56, 49, 65 (25, 24, 24, 24)	58 (12)	48, 50, 60, 53 (25, 24, 23, 23)
6% AMD	36 (26)	35 (24)	38 (26)	42, 40 (26, 26)
9% AMD	42 (25)	31 (26)	43 (26)	43, 41 (26, 25)
12% AMD	40 (24)	40 (24)	-	44 (24)
6% AMD 2% Lime	37, 38, 38 (21, 21, 21)	30, 28, 37 (21, 21, 21)	-	32, 32 (22, 21)
12% AMD 2% Lime	34, 36, 35 (25, 25, 25)	32, 34 (24, 24)	-	26, 31, 34 (24, 25, 24)
6% AMD 4% Kiln Dust	-	47, 47, 44 (20, 20, 19)	-	51, 34, 51 (19, 21, 20)

WHARTON SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
6% AMD 8% Kiln Dust	-	51, 56, 82 (21, 22, 22)	-	50, 47, 61 (22, 22, 20)
12% AMD 4% Kion Dust	-	31, 47, 38 (22, 21, 20)	-	41, 38, 38 (20, 22, 22)
12% AMD 8% Kiln Dust	-	47, 45, 49 (23, 25, 24)	-	54, 51, 34 (25, 25, 28)
Freeze-Thaw 6% AMD	-	2, 3 (38, 41)	-	-
Freeze-Thaw 6% AMD 2% Lime	-	5, 4, 5 (33, 37, 27)	-	-

C. Class III Soils

CHOBEE SERIES
FINE-LOAMY, MIXED, NONCALCAREOUS, HYPERTHERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	48, 46, 46 (19, 19, 19)	-	51, 49, 51 (18, 17, 18)
6% Lime	-	71 (18)	-	82, 92, 95 (20, 19, 17)
6% PG1	-	47, 42, 51 (19, 19, 18)	-	52, 48, 44 (17, 18, 18)
12% PG1	-	37, 38, 33 (20, 21, 21)	-	45, 36, 35 (19, 19, 20)
6% PG1 6% Lime	-	60 (18)	-	119, 93 (17, 18)
12% PG1 12% Lime	-	63 (18)	-	30 (23)

CRAVEN SERIES
CLAYEY, MIXED, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	53 (24)	56 (24)	56 (25)	60, 51 (24, 24)
6% Lime	-	95, 96, 93 (24, 24, 24)	-	173, 177, 148 (23, 23, 24)
6% PG2	40 (26)	36 (26)	41 (25)	38, 38 (26, 26)
9% PG2	52 (22)	40 (23)	42 (23)	45, 49 (23, 23)
12% PG2	50 (23)	49 (23)	42 (24)	44, 43 (23, 22)
6% PG2 6% Lime	84, 91, 65 (28, 25, 24)	126, 141, 136 (23, 23, 23)	-	170, 90, 181 (24, 25, 23)
12% PG2 6% Lime	78, 80, 86 (26, 26, 25)	101, 104, 92 (24, 25, 25)	-	61, 41, 58 (27, 28, 27)
2% PG2 2% Lime 4% Fly Ash	-	94, 111, 110 (25, 25, 25)	-	96, 95, 106 (25, 25, 25)
2% PG2 6% Lime 4% Fly Ash	-	203, 179, 190 (24, 24, 24)	-	212, 185, 225 (25, 26, 24)
4% PG2 2% Lime 8% Fly Ash	-	90, 90, 76 (27, 27, 27)	-	65, 99, 65 (28, 27, 28)
4% PG2 6% Lime 8% Fly Ash	-	196, 188, 232 (26, 26, 26)	-	220, 203, 253 (27, 28, 25)

HARTWELL SERIES
FINE, MIXED, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	42, 49, 49 (20, 21, 20)	43, 50, 26 (21, 20, 22)	41, 48, 56 (21, 21, 20)	43, 48, 46 (23, 21, 20)
6% FG2	41, 43, 41 (21, 21, 21)	45, 52, 46 (20, 20, 21)	48, 45, 48 (21, 21, 21)	43, 43, 44 (21, 21, 20)
9% FG2	44, 43, 51 (18, 18, 18)	55, 52, 44 (18, 18, 18)	44, 48, 48 (18, 18, 18)	44, 52 (18, 18)
12% FG2	46, 39, 40 (17, 18, 18)	43, 43, 53 (18, 18, 18)	57, 46 (17, 17)	41, 45, 47 (18, 18, 19)

HIGGINSVILLE SERIES
FINE-SILTY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	50 (25)	46 (25)	35, 44, 40 (25, 25, 26)	44, 42, 45 (26, 26, 26)
2% Lime	37 (22)	-	33 (23)	21 (23)
6% Lime	-	57, 54, 49 (24, 24, 27)	-	54, 59, 37 (24, 24, 24)
6% Kiln Dust	-	37, 30, 39 (21, 21, 21)	-	24, 39, 26 (25, 21, 21)
6% FG1 2% Lime	42 (23)	-	53 (24)	46 (24)
6% FG1 2% Lime	51, 58, 52 (25, 25, 25)	44, 42, 41 (25, 30, 25)	-	45, 39, 46 (25, 24, 25)
12% FG1 2% Lime	-	-	37 (24)	36 (24)
12% FG1 2% Lime	50, 43 (25, 25)	49, 40, 38 (26, 25, 25)	-	57, 52, 52 (25, 25, 25)
6% FG2	48 (21)	50 (21)	58, 57, 51 (21, 20, 23)	43, 47, 52 (22, 21, 21)
9% FG2	52 (22)	48 (22)	46, 54, 47 (22, 23, 23)	54, 45 (22, 22)
12% FG2	52 (21)	58 (21)	53, 56, 53 (21, 21, 21)	48, 47 (20, 21)
6% FG2 2% Lime	38, 36 (20, 21)	40 (21)	-	30, 28 (21, 21)
12% FG2 2% Lime	50 (19)	40 (21)	-	12, 34 (24, 26)

HIGGINSVILLE SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
6% FG2 4% Kiln Dust	-	49, 52, 54 (23, 23, 23)	-	48, 49, 52 (22, 23, 23)
6% FG2 8% Kiln Dust	-	95, 96, 72 (23, 23, 23)	-	109, 103, 118 (22, 23, 22)
12% FG2 4% Kiln Dust	-	47, 49, 61 (22, 22, 22)	-	53, 61, 53 (22, 22, 22)
12% FG2 8% Kiln Dust	-	109, 111, 129 (23, 23, 23)	-	118, 143, 126 (23, 23, 23)

KATY SERIES
FINE-LOAMY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	54, 45, 56 (21, 21, 21)	53, 51, 49 (20, 20, 20)	53, 51, 58 (21, 21, 21)	42, 43, 50 (21, 21, 21)
6% Lime	-	68, 63 (19, 20)	-	94, 74, 79 (21, 19, 21)
6% PG3	55, 50, 45 (21, 21, 21)	48, 47, 51 (21, 22, 21)	43, 46, 44 (23, 22, 22)	44, 47, 49 (22, 22, 22)
9% PG3	49, 51 (18, 18)	38, 42, 41 (18, 18, 19)	40, 39, 47 (18, 18, 18)	36, 41, 42 (19, 18, 19)
12% PG3	48, 47 (20, 19)	40, 45, 38 (19, 19, 19)	38, 39, 35 (19, 19, 20)	39, 41, 37 (19, 19, 20)
6% PG3 6% Lime	68, 57, 55 (15, 15, 16)	74, 80, 91 (15, 15, 15)	-	153, 144, 114 (14, 15, 14)
12% PG3 6% Lime	58, 56, 59 (19, 20, 19)	100, 108, 108 (18, 19, 20)	-	23, 119, 15 (34, 18, 35)
2% PG3 2% Lime 4% Fly Ash	-	103, 96, 104 (20, 19, 20)	-	66, 115, 97 (21, 19, 20)
2% PG3 6% Lime 4% Fly Ash	-	161, 156, 169 (21, 20, 20)	-	162, 173, 158 (20, 21, 20)
4% PG3 2% Lime 8% Fly Ash	-	86, 96, 96 (21, 21, 21)	-	105, 118, 54 (21, 21, 22)
4% PG3 6% Lime 8% Fly Ash	-	179, 139, 172 (21, 21, 20)	-	172, 206, 257 (21, 21, 20)

UPSHUR SERIES
FINE, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	40 (21)	39 (23)	38 (22)	30, 33 (23, 23)
2% Lime	38 (22)	36 (22)	37 (22)	34 (22)
6% FGl 2% Lime	44 (20)	53 (20)	48 (20)	25 (22)
12% FGl 2% Lime	38 (19)	40 (20)	-	43 (20)
6% AMD	37 (21)	40 (22)	41 (22)	40, 43 (22, 23)
9% AMD	40 (22)	41 (21)	39 (21)	38 (22)
12% AMD	33 (22)	35 (21)	40 (19)	20, 34 (26, 23)

D. Class IV Soils

FELLOWSHIP SERIES
FINE, MONTMORILLONITIC, HYPERTHERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	41, 40, 42 (29, 29, 29)	-	46, 38, 43 (29, 28, 28)
6% Lime	-	28, 35 (28, 28)	-	29, 35, 33 (29, 28, 28)
6% Cement	-	67 (26)	-	58, 40 (26, 27)
6% PG1	-	40, 38, 39 (30, 29, 30)	-	35, 40, 41 (30, 30, 30)
12% PG1	-	41, 37, 46 (27, 28, 27)	-	39, 38, 37 (27, 27, 27)
6% PG1 6% Lime	49, 50, 48 (41, 41, 42)	40, 36, 35 (42, 42, 42)	-	19, 20, 23 (42, 41, 42)
12% PG1 6% Lime	48, 54, 59 (38, 39, 39)	38, 44, 39 (39, 39, 39)	-	22, 25, 26 (39, 40, 40)
2% PG1 2% Lime 4% Fly Ash	-	27, 26, 26 (28, 28, 29)	-	13, 21, 24 (29, 29, 30)
2% PG1 6% Lime 4% Fly Ash	-	41, 42, 49 (27, 26, 27)	-	32, 41, 32 (27, 27, 27)
4% PG1 2% Lime 8% Fly Ash	-	28, 30, 30 (29, 28, 27)	-	20, 20, 26 (28, 29, 30)
4% PG1 6% Lime 8% Fly Ash	-	64, 54 (26, 25)	-	40, 46 (27, 27)
6% PG1 6% Cement	-	116 (26)	-	59, 40, 62 (26, 28, 26)
12% PG1 6% Cement	-	52 (25)	-	47, 23, 33 (25, 29, 27)

LAKE CHARLES SERIES
FINE, MONTMORILLONITIC, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	48, 51, 49 (25, 24, 25)	45, 49, 45 (24, 24, 25)	50, 45, 45 (24, 24, 24)	50, 49, 40 (24, 24, 24)
6% PG3	68 (20)	64 (21)	56 (21)	59, 47 (22, 21)
9% PG3	56 (21)	60 (22)	52 (22)	50, 56 (20, 22)
12% PG3	55 (20)	45 (20)	52 (21)	47, 49 (21, 20)

SHARKEY SERIES
VERY FINE, MONTMORILLONITIC, NONACID, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	48 (25)	50 (26)	58 58 (28)	51, 59 (27, 28)
6% Lime	-	21, 27 (24, 25)	-	36, 33, 31 (23, 23, 24)
6% PG1 6% Lime	-	33 (26)	-	57, 32 (26, 26)
12% PG1 6% Lime	-	24 (26)	-	-
6% PG3	57 (29)	50 (32)	42 (31)	52, 51 (29, 30)
9% PG3	60 (27)	52 (26)	56 (27)	51, 52 (28, 28)
12% PG3	45 (32)	46 (31)	46 (32)	38, 45 (32, 32)
6% PG3 6% Lime	29 (25)	50, 43 (25, 25)	-	65, 31, 70 (25, 27, 25)
12% PG3 6% Lime	47, 50, 51 (32, 31, 31)	94, 98, 95 (30, 31, 31)	-	107, 112, 48 (37, 32, 37)

SHARPSBURG SERIES
FINE, MONTMORILLONITIC, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	41 (21)	55, 55, 49 (22, 21, 22)	47, 54, 51 (21, 21, 21)	45, 48, 49 (21, 22, 22)
None	53, 51, 48 (23, 23, 23)	47, 52, 48 (23, 23, 23)	49, 56, 49 (24, 26, 23)	47, 50, 54, 54, 40, 48 (23, 23, 23, 23, 23, 23)
2% Lime	34 (20)	34 (21)	-	40 (28)
6% Lime	-	36, 42, 45 (21, 21, 21)	-	49, 54, 46 (21, 21, 21)
6% Kiln Dust	-	58, 48, 70 (20, 20, 20)	-	63, 62, 58 (20, 20, 19)
6% PG2	43 (26)	39 (25)	43 (26)	41, 40 (26, 26)
9% PG2	39 (26)	40 (26)	42 (26)	39, 38 (26, 27)
12% PG2	33 (26)	40 (26)	34 (26)	34, 33 (28, 28)
6% PG2 6% Lime	50, 51, 47 (23, 24, 23)	106, 91, 87 (22, 22, 23)	-	129, 116, 62 (23, 24, 27)
12% PG2 6% Lime	52, 52, 48 (24, 25, 24)	91, 91, 83 (23, 23, 23)	-	116, 127, 108 (24, 23, 24)
2% PG2 2% Lime 4% Fly Ash	-	58, 52, 54 (23, 22, 22)	-	54, 45, 46 (23, 23, 23)
2% PG2 6% Lime 4% Fly Ash	-	79, 80, 68 (21, 21, 21)	-	36, 38, 54 (24, 23, 22)

SHARPSBURG SERIES (Continued)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
4% PG2 2% Lime 8% Fly Ash	-	42, 58 (22, 22)	-	62, 83, 74 (21, 22, 21)
4% PG2 6% Lime 8% Fly Ash	-	91, 94, 79 (22, 22, 27)	-	85, 115, 105 (24, 21, 21)
6% PG3	42 (26)	42 (26)	40 (26)	43, 40 (26, 26)
9% PG3	50 (23)	44 (23)	44 (23)	44, 50 (24, 24)
12% PG3	45 (24)	47 (23)	49 (24)	48, 47 (24, 24)
6% PG3 6% Lime	56, 43, 46 (24, 23, 23)	93, 92, 80 (23, 23, 23)	-	54, 114, 108[a/] (28, 23, 22)
12% PG3 6% Lime	45, 43, 38 (22, 22, 22)	63, 61, 66 (22, 22, 22)	-	67, 26, 56 (22, 29, 22)
6% FG1 2% Lime	55 (24)	59 (24)	-	50, 49 (23, 24)
6% FG1 2% Lime	44, 41, 41 (24, 24, 24)	45, 48, 51 (24, 24, 23)	-	49, 57, 38 (24, 24, 24)
12% FG1 2% Lime	41 (24)	50 (25)	-	39, 42, 49 (25, 24, 25)
12% FG1 2% Lime	48, 44, 44 (23, 24, 23)	42, 44, 53 (24, 23, 24)	-	52, 36, 52 (23, 25, 23)
6% FG2	40 (22)	43, 41, 47 (23, 23, 23)	41, 49, 44 (23, 23, 23)	40, 45, 47 (22, 22, 22)

SHARPSBURG SERIES (Continued)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
9% FG2	39, 33, 47 (18, 18, 18)	41, 33, 37 (17, 18, 18)	43, 38, 42 (18, 18, 18)	46, 38, 40 (18, 18, 18)
12% FG2	50, 48, 38 (19, 19, 18)	37, 36, 46 (18, 18, 18)	35, 62, 40 (19, 19, 19)	36, 38, 47 (19, 18, 18)
6% FG2 2% Lime	36, 48, 63 (22, 22, 22)	64, 58, 56 (22, 22, 22)	-	43, 49, 52 (22, 22, 22)
12% FG2 2% Lime	52, 48, 50 (20, 20, 20)	39, 37, 41 (21, 20, 21)	-	50, 56, 56 (20, 20, 20)
6% FG2 4% Kiln Dust	-	56, 52, 58 (20, 20, 20)	-	58, 59, 51 (18, 20, 19)
6% FG2 8% Kiln Dust	-	68, 77, 68 (18, 20, 20)	-	79, 98, 82 (18, 20, 20)
12% FG2 4% Kiln Dust	-	55, 70 (19, 19)	-	67, 70, 62 (19, 19, 20)
12% FG2 8% Kiln Dust	-	83, 82, 97 (21, 20, 20)	-	98, 96, 78 (20, 20, 22)
6% AMD	47 (26)	45 (26)	44 (26)	39, 45 (26, 26)
9% AMD	43 (28)	43 (27)	40 (26)	46, 41 (27, 26)
12% AMD	39 (28)	38 (27)	41 (29)	45, 39 (27, 28)
6% AMD 2% Lime	28, 27, 30 (24, 24, 24)	28, 24, 28 (24, 24, 24)	-	30, 39, 31 (23, 24, 23)
12% AMD 2% Lime	28, 28, 28 (24, 24, 24)	30, 26, 23 (25, 24, 25)	-	31, 26 (24, 25)

SHARPSBURG SERIES (Concluded)

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
Freeze-Thaw 6% PG2	-	4, 3 (33, 33)	-	-
Freeze-Thaw 6% PG2 6% Lime	-	40, 33, 40 (42, 42, 43)	-	-
Freeze-Thaw 6% FG2	-	4, 4, 5 (53, 34, 34)	-	-
Freeze-Thaw 6% FG2 2% Lime	-	28, 23, 28 (33, 35, 36)	-	-

SUMMIT SERIES
FINE, MONTMORILLONITIC, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	39, 51, 51 (25, 26, 26)	47 (25)	50, 50, 49 (26, 26, 27)	51, 43, 46 (26, 28, 26)
6% Lime	-	45, 41, 41 (22, 22, 22)	-	59, 45, 47 (22, 22, 22)
6% Kiln Dust	-	64, 81, 58 (22, 23, 24)	-	55, 74, 65 (25, 24, 23)
6% FG2	41, 51, 46 (22, 22, 21)	46 (22)	47 (22)	43, 43, 49 (22, 22, 22)
9% FG2	53, 54, 49 (23, 23, 23)	55 (23)	66, 53, 60 (23, 24, 24)	50, 60, 56 (24, 23, 23)
12% FG2	38, 45, 61 (17, 17, 16)	41 (18)	47, 49, 33 (18, 18, 18)	53, 53, 41 (17, 18, 18)
6% FG2 2% Lime	37, 36, 30 (22, 22, 21)	52, 39, 45 (21, 21, 21)	-	57, 32, 54 (21, 24, 21)
12% FG2 2% Lime	38, 33 (20, 20)	40, 44 (20, 20)	-	50, 42 (20, 20)
6% FG2 4% Kiln Dust	-	60, 44, 44 (20, 20, 20)	-	30, 42, 45 (22, 23, 20)
6% FG2 8% Kiln Dust	-	68, 84 (19, 19)	-	71, 91, 98 (20, 19, 19)
12% FG2 4% Kiln Dust	-	55, 62 (21, 21)	-	27, 51, 68 (23, 21, 21)
12% FG2 8% Kiln Dust	-	92, 112, 100 (24, 21, 21)	-	128, 146, 134 (21, 21, 21)

APPENDIX D

MULTIPLE REGRESSION ANALYSIS
COMPUTATION PROCEDURES

MULTIPLE REGRESSION ANALYSIS COMPUTATION PROCEDURES

The unconfined compression strength data generated during the program were subjected to multiple regression analysis to determine the significance of various parameters on the measured strengths. The procedures used for the multiple regression analysis are those reported by Kramer.[1/] An outline of the procedure is presented below, followed by a sample calculation using the Exum/PG2/lime system.

Algebraic Procedure

The method will be illustrated by considering four independent variables (x_1, x_2, x_3, and x_4) and one dependent variable (y). First compute and record the sums of squares and sums of products in the following symmetric matrix.

$$\left|\begin{array}{ccccc} a_{11} & a_{12} & a_{13} & a_{14} & a_{1y} \\ & a_{22} & a_{23} & a_{24} & a_{2y} \\ & & a_{33} & a_{34} & a_{3y} \\ & & & a_{44} & a_{4y} \\ & & & & a_{yy} \end{array}\right| \qquad (1)$$

where $$a_{ii} = \sum_{\alpha=1}^{n} x_{i\alpha}^2 - \frac{\left(\sum_{\alpha=1}^{n} x_{i\alpha}\right)^2}{n}$$

1/ Kramer, C. Y., "Simplified Computations for Multiple Regression," in the CRC Handbook of Tables of Probability and Statistics, Chemical Rubber Company, Cleveland, Ohio, pp. 41-46 (1966).

$$a_{ij} = \sum_{\alpha=1}^{n} x_{i\alpha}x_{j\alpha} - \frac{\left(\sum_{\alpha=1}^{n} x_{i\alpha} \sum_{\alpha=1}^{n} x_{j\alpha}\right)}{n}$$

$$a_{iy} = \sum_{\alpha=1}^{n} x_{i\alpha}y_{\alpha} - \frac{\left(\sum_{\alpha=1}^{n} x_{i\alpha} \sum_{\alpha=1}^{n} y_{\alpha}\right)}{n}$$

$$a_{yy} = \sum_{\alpha=1}^{n} y_{\alpha}^2 - \frac{\left(\sum_{\alpha=1}^{n} y_{\alpha}\right)^2}{n}$$

i, j = 1, 2, 3, and 4; and n is number of observations.

In order to simplify the calculations and ensure carrying enough significant figures, the diagonal terms (a_{11}, a_{22}, a_{33}, a_{44}, and a_{yy}) are made to lie between 0.1 and 10 by pre- and post-multiplying matrix 1 by a diagonal matrix of powers of 10.

$$\begin{vmatrix} 10^{q_1} & 0 & 0 & 0 & 0 \\ 0 & 10^{q_2} & 0 & 0 & 0 \\ 0 & 0 & 10^{q_3} & 0 & 0 \\ 0 & 0 & 0 & 10^{q_4} & 0 \\ 0 & 0 & 0 & 0 & 10^{p} \end{vmatrix} \qquad (2)$$

The exponents q_i and p are powers of 10 which will make each diagonal element lie between 0.1 and 10 when matrix 1 is pre- and post-multiplied by matrix 2. This matrix multiplication will yield a new working matrix having the following form.

$$\left|\begin{array}{ccccc} a^*_{11} & a^*_{12} & a^*_{13} & a^*_{14} & a^*_{1y} \\ & a^*_{22} & a^*_{23} & a^*_{24} & a^*_{2y} \\ & & a^*_{33} & a^*_{34} & a^*_{3y} \\ & & & a^*_{44} & a^*_{4y} \\ & & & & a^*_{yy} \end{array}\right| \qquad (3)$$

where $a^*_{ii} = 10^{2q_i} a_{ii}$

$a^*_{ij} = 10^{(q_i + q_j)} a_{ij}$

$a^*_{iy} = 10^{(q_i + p)} a_{iy}$

$a^*_{yy} = 10^{2p} a_{yy}$

Matrix 3 is then reduced by the Abbreviated Doolittle Method, which solves the symmetric matrix for coefficients of independent variables.

Procedure for the Abbreviated Doolittle Method

The Abbreviated Doolittle Method for solving symmetric matrices involves a number of checks which serve as flags in the event of arithmetic error. The first check is realized by summing the elements in the various rows of the matrix, keeping in mind that the column elements above a diagonal element are row elements of the symmetric matrix. Thus matrix 3 is rewritten:

a^*_{11}	a^*_{12}	a^*_{13}	a^*_{14}	a^*_{1y}	a^*_{1c}
	a^*_{22}	a^*_{23}	a^*_{24}	a^*_{2y}	a^*_{2c}
		a^*_{33}	a^*_{34}	a^*_{3y}	a^*_{3c}
			a^*_{44}	a^*_{4y}	a^*_{4c}
				a^*_{yy}	a^*_{yc}

(4)

where $a^*_{ic} = \sum_{\alpha=1}^{n} (a^*_{i\alpha} + a^*_{iy})$

We then compute for matrix 4:

A_{11}	A_{12}	A_{13}	A_{14}	A_{1y}	A_{1c}	
B_{11}	B_{12}	B_{13}	B_{14}	B_{1y}	B_{1c}	ΣB_{1j} $(j = 1, 2, 3, 4, y)$
	A_{22}	A_{23}	A_{24}	A_{2y}	A_{2c}	ΣA_{2j} $(j = 2, 3, 4, y)$
	B_{22}	B_{23}	B_{24}	B_{2y}	B_{2c}	ΣB_{2j} $(j = 2, 3, 4, y)$
		A_{33}	A_{34}	A_{3y}	A_{3c}	ΣA_{3j} $(j = 3, 4, y)$
		B_{33}	B_{34}	B_{3y}	B_{3c}	ΣB_{3j} $(j = 3, 4, y)$
			A_{44}	A_{4y}	A_{4c}	ΣA_{4j} $(j = 4, y)$
			B_{44}	B_{4y}	B_{4c}	ΣB_{4j} $(j = 4, y)$
				A_{4y}	A_{4c}	

(5)

where $A_{1j} = a^*_{1j}$

$B_{1j} = A_{ij}/A_{11}$

$A_{2j} = a^*_{2j} - A_{12}B_{1j}$

$$B_{2j} = A_{2j}/A_{22}$$

$$A_{3j} = a^*_{3j} - A_{13}B_{1j} - A_{23}B_{2j}$$

$$B_{3j} = A_{3j}/A_{33}$$

$$A_{4j} = a^*_{4j} - A_{14}B_{1j} - A_{24}B_{2j} - A_{23}B_{3j}$$

$$B_{4j} = A_{4j}/B_{4j}$$

$$A_{yj} = a^*_{yj} - A_{1y}B_{1j} - A_{2y}B_{2j} - A_{3y}B_{3j} - A_{4y}B_{4j}$$

If the ΣA_{ij}'s or ΣB_{ij}'s do not equal the corresponding A_{ic} or B_{ic} value, then a mistake has been made in the arithmetic which can be caught before proceeding on. Upon completion of the arithmetic, the value of A_{yc} should equal A_{yy} to several significant figures.

Calculation of Correlation Coefficient

At this point, the index of determination, r^2, can be calculated indicating the overall fit among independent variables to the dependent variables:

$$r2 = \frac{a^*_{yy} - A_{yy}}{a^*_{yy}} \qquad (6)$$

If r^2 is near unity, the fit is very good. The correlation coefficient, r , can be determined by taking the square root. Standard tables of the correlation coefficient (at n - 5 degrees of freedom for the case with four independent variables) will give the statistical goodness of fit for the correlation.

Determination of Regression Coefficients

The preceeding computations can be used to calculate the regression coefficients which relate the independent variables to the dependent variables. Since the original matrix (1) was modified to a working matrix (3), one first computes modified regression coefficients, b^*_i. These coefficients are:

$$
\begin{aligned}
b_4^* &= B_{4y} \\
b_3^* &= B_{3y} - b_4^* B_{34} \\
b_2^* &= B_{2y} - b_3^* B_{23} - b_4^* B_{24} \\
b_1^* &= B_{1y} - b_2^* B_{12} - b_3^* B_{13} - b_4^* B_{14}
\end{aligned}
\tag{7}
$$

At this point, another check on the calculations can be made, since $\sum_{i=1}^{4} b_i^* a_{iy}^* = A_{yy}$.

The true regression coefficients, b_i , are computed using the exponents q_i and p in matrix 2. They are:

$$
\begin{aligned}
b_1 &= 10^{(q_1-p)} b_1^* \\
b_2 &= 10^{(q_2-p)} b_2^* \\
b_3 &= 10^{(q_3-p)} b_3^* \\
b_4 &= 10^{(q_4-p)} b_4^*
\end{aligned}
\tag{8}
$$

The regression constant, k , can be calculated by the following procedure:

$$
k = \frac{\sum_{\alpha=1}^{n} y_\alpha - b_1 \sum_{\alpha=1}^{n} x_{1\alpha} - b_2 \sum_{\alpha=1}^{n} x_{2\alpha} - b_3 \sum_{\alpha=1}^{n} x_{3\alpha} - b_4 \sum_{\alpha=1}^{n} x_{4\alpha}}{n} \tag{9}
$$

where n is the population used in the regression analysis.

Thus, one finally obtains the relationship between the independent variables and dependent variables as:

$$
y = k + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 \tag{10}
$$

Determination of Regression Coefficient Standard Deviations

At this point, one has computed the relationship between the several independent variables and one dependent variable by (10), and the overall correlation of the regression by (6). One does not know the significance of the individual regression coefficients. The significance can be established by determining the standard deviation of each of the regression coefficients.

The standard deviation is determined using the inverse of the matrix (3) elements involving only the independent variables.

$$\begin{vmatrix} c^*_{11} & c^*_{12} & c^*_{13} & c^*_{14} \\ & c^*_{22} & c^*_{23} & c^*_{24} \\ & & c^*_{33} & c^*_{34} \\ & & & c^*_{44} \end{vmatrix} \qquad (11)$$

where
$$\begin{aligned} c^*_{44} &= 1/A_{44} \\ c^*_{34} &= -c^*_{44}B_{34} \\ c^*_{24} &= -c^*_{34}B_{23} - c^*_{44}B_{24} \\ c^*_{14} &= c^*_{24}B_{12} - c^*_{34}B_{13} - c^*_{44}B_{14} \end{aligned} \qquad (12)$$

Another check is applied here by computing $\sum_{i=1}^{4} c^*_{4i} a^*_{4i}$ which should be equal to unity.

Similarly,

$$\begin{aligned} c^*_{33} &= 1/A_{33} - c^*_{34}B_{34} \\ c^*_{23} &= -c^*_{33}B_{23} - c^*_{34}B_{24} \\ c^*_{13} &= -c^*_{23}B_{12} - c^*_{33}B_{13} - c^*_{34}B_{14} \end{aligned} \qquad (13)$$

Again, $\sum_{i=1}^{4} c^*_{3i} a^*_{3i}$ should be equal to unity.

As before,

$$c^*_{22} = 1/A_{22} - c^*_{23}B_{23} - c^*_{24}B_{24}$$
$$c^*_{12} = -c^*_{22}B_{12} - c^*_{23}B_{13} - c^*_{24}B_{14} \qquad (14)$$

And, $\sum_{i=1}^{4} c^*_{2i}a^*_{2i}$ should be equal to one.

Finally,

$$c^*_{11} = 1/A_{11} - c^*_{12}B_{12} - c^*_{13}B_{13} - c^*_{14}B_{14} \qquad (15)$$

The sum $\sum_{i=1}^{4} c^*_{1i}a^*_{1i}$ should once more be unity.

The standard deviations are related to the diagonal c^*_{ii} elements. Since the computations are based upon the working matrix (3), they must be converted to their real values by using the exponents of matrix (2). The conversions are:

$$c_{11} = 10^{2q_1}c^*_{11}$$
$$c_{22} = 10^{2q_2}c^*_{22}$$
$$c_{33} = 10^{2q_3}c^*_{33} \qquad (16)$$
$$c_{44} = 10^{2q_4}c^*_{44}$$

The variances for the regression coefficients are found by multiplying the appropriate c_{ii} by the residual mean square (RMS) of the equation. The RMS for the case of four independent variables and one dependent variable is:

$$RMS = \frac{10^{-2p}A_{yy}}{n-5} \qquad (17)$$

where n is the population of individual data in the analysis. The value 5 is one more than the number of independent variables of the analysis. Standard Deviations (SD_i) are determined by taking the square root of the variances. Thus,

$$\begin{aligned} SD_1 &= \sqrt{RMS \cdot c_{11}} \\ SD_2 &= \sqrt{RMS \cdot c_{22}} \\ SD_3 &= \sqrt{RMS \cdot c_{33}} \\ SD_4 &= \sqrt{RMS \cdot c_{44}} \end{aligned} \qquad (18)$$

Significance of Regression Coefficients

Following computation of the regression coefficients by (8) and the standard deviation by (18), the statistical significance of the coefficients can be determined using the "Student-t" test. The ratio of the standard deviation to the regression coefficient gives the statistical "Student-t" factor. By comparing the computed "Student-t" to values in standard tables, the statistical significance of the regression coefficient is established. If the computed value is greater than that found in the table, then the regression coefficient is statistically significant at a level of confidence greater than that indicated. The computed "Student-t" factors are thus:

$$\begin{aligned} t_1 &= b_1/SD_1 \\ t_2 &= b_2/SD_2 \\ t_3 &= b_3/SD_3 \\ t_4 &= b_4/SD_4 \end{aligned} \qquad (19)$$

Example Calculation (Exum/PG2/lime)

The following presentation is an example calculation using the procedures described above. The example used is the Exum/PG2/lime system, and will show how the equations plotted in Figure 23 were developed, and how standard deviations and statistical significances reported in Table 31 were established. Four computations are involved: untreated Exum soil, Exum/lime, Exum/PG3, and Exum/PG3/lime. The dependent variable (y) in all four cases is unconfined compressive strength in psi. Independent variables include moisture content (% H_2O) and curing time (days) in all cases; concentration of additive (% SW and % lime) are used where appropriate.

Untreated Exum Soil

Raw data (% H_2O, days, psi):

(16, 1, 33)
(16, 7, 34)
(17, 14, 32)
(16, 28, 32)
(16, 28, 33)

$\Sigma y = \Sigma$ psi $= 162$ $\quad\quad$ $\Sigma y^2 = \Sigma$ psi$^2 = 5{,}258$

$\Sigma x_1 = \Sigma$ % $H_2O = 81$ $\quad\quad$ $\Sigma x_1^2 = \Sigma$ % $H_2O^2 = 1{,}313$

$\Sigma x_2 = \Sigma$ days $= 78$ $\quad\quad$ $\Sigma x_2^2 = \Sigma$ days$^2 = 1{,}814$

$\Sigma x_1 x_2 = \Sigma$ % $H_2O \cdot$ days $= 1{,}262$

$\Sigma x_1 y = \Sigma$ % $H_2O \cdot$ psi $= 2{,}622$

$\Sigma x_2 y = \Sigma$ days $\cdot$ psi $= 2{,}511$

n = population = 5

Establish matrix (1):

$$\begin{array}{ccc|} 0.8000 & -1.6000 & -2.4000 \\ & 597.2000 & -16.2000 \\ & & 9.2000 \end{array}$$

Exponents in matrix (2):

$q_1 = 0; \quad q_2 = -1; \quad p = 0$

Compute working matrices (3) and (4):

0.8000	-0.1600	-2.4000	-1.7600
	5.9720	-1.6200	4.1920
		9.2000	5.1800

Derive matrix (5):

0.8000	-0.1600	-2.4000	-1.7600	
1.0000	-0.2000	-3.0000	-2.2000	-2.2000
	5.9400	-2.1000	3.8400	3.8400
	1.0000	-0.3535	0.6465	0.6465
		1.2577	1.2577	

Calculate index of determination, r^2 , and correlation coefficent, r , by (6):

$$r^2 = \frac{9.200 - 1.2577}{9.200} = 0.863$$

$$r = \sqrt{0.863} = 0.929$$

Calculate regression coefficients by (7) and (8):

b_1 (psi/% H_2O) = -3.07

b_2 (psi/day) = -0.04

(These values are reported for moisture and time for the Exum control in Table 31.)

Establish regression equation (10):

psi = 83 - 3.07 (% H_2O) - 0.04 (days)

Under the experimental moisture conditions, the equation becomes (a) in Figure 23:

$$psi = 33 - 0.04 \text{ (days)}$$

Compute inverse matrix (11):

$$\begin{vmatrix} 1.2567 & 0.0337 \\ & 0.1684 \end{vmatrix}$$

Determine actual values if diagonal terms by (16):

$$c_{11} = 1.2567$$

$$c_{22} = 0.001684$$

Compute residual mean square by (17):

$$RMS = \frac{1.2577}{5 - 3} = 0.6289$$

Compute standard deviation for b_1 and b_2 by equation (18):

$$SD_1 \text{ (\% } H_2O) = 0.89$$

$$SD_2 \text{ (days)} = 0.03$$

(These values are reported for Exum control in Table 31.)

Compute ratios of regression coefficients to standard deviations by (19):

$$t_1 \text{ (\% } H_2O) = \frac{3.07}{0.89} = 3.45$$

$$t_2 \text{ (days)} = \frac{0.04}{0.03} = 1.33$$

At two degrees of freedom (5 - 3) and 90% confidence level, the "Student't" value is 2.92; at the 95% level, "Student-t" is 4.30. The ratio for time (1.33) is less than 2.92; thus, time is not significant at the 90% confidence level. The moisture ratio (3.45) is between 2.92 and 4.30. Therefore, the moisture coefficient is significant at the 90% level but not the 95% level.

Exum/Lime

Raw data generated from Exum/lime specimens are used in conjunction with those obtained from untreated soil specimens. The data from Exum/lime specimens are (% H_2O, days, % lime, psi):

(18, 7, 6, 65) (18, 28, 6, 96)
(18, 7, 6, 70) (18, 28, 6, 123)
(18, 7, 6, 60) (17, 28, 6, 110)

$\Sigma y = \Sigma$ psi $= 524$ $\Sigma y^2 = \Sigma$ psi$^2 = 49,170$

$\Sigma x_1 = \Sigma$ % $H_2O = 106$ $\Sigma x_1^2 = \Sigma$ % $H_2O^2 = 1,874$

$\Sigma x_2 = \Sigma$ days $= 105$ $\Sigma x_2^2 = \Sigma$ days$^2 = 2,499$

$\Sigma x_3 = \Sigma$ % lime $= 36$ $\Sigma x_3^2 = \Sigma$ % lime$^2 = 216$

$\Sigma x_1x_2 = \Sigma$ % $H_2O \cdot$ days $= 1,834$

$\Sigma x_1x_3 = \Sigma$ % $H_2O \cdot$ % lime $= 636$

$\Sigma x_2x_3 = \Sigma$ days $\cdot$ % lime $= 630$

$\Sigma x_1y = \Sigma$ % $H_2O \cdot$ psi $= 9,199$

$\Sigma x_2y = \Sigma$ days $\cdot$ psi $= 10,577$

$\Sigma x_3y = \Sigma$ % lime $\cdot$ psi $= 3,144$

n = population = 6

Add Exum/lime values to the corresponding values for untreated soil:

$\Sigma y = \Sigma$ psi $= 686$ $\Sigma y^2 = \Sigma$ psi$^2 = 54,428$

$\Sigma x_1 = \Sigma$ % $H_2O = 187$ $\Sigma x_1^2 = \Sigma$ % $H_2O^2 = 3,187$

$\Sigma x_2 = \Sigma$ days $= 183$ $\Sigma x_2^2 = \Sigma$ days$^2 = 4,313$

$\Sigma x_3 = \Sigma$ % lime $= 36$ $\Sigma x_3^2 = \Sigma$ % lime$^2 = 216$

Σx_1x_2 = Σ % H_2O · days = 3,096

Σx_1x_3 = Σ % H_2O · % lime = 636

Σx_2x_3 = Σ days · % lime = 630

Σx_1y = Σ % H_2O · psi = 11,821

Σx_2y = Σ days · psi = 13,088

Σx_3y = Σ % lime · psi = 3,144

n = population = 6 + 5 = 11

Establish matrix (1):

8.000	-15.0000	24.0000	159.0000
	1,268.5455	31.0909	1,675.4546
		98.1818	898.9091
			11,646.5455

Exponents for matrix (2):

$q_1 = 0$; $q_2 = -2$; $q_3 = -1$; $p = -2$

Compute working matrices (3) and (4):

8.0000	-0.1500	2.4000	1.5900	11.8400
	0.1269	0.0311	0.1675	0.1755
		0.9818	0.8989	4.3118
			1.1647	3.8211

Derive matrix (5):

8.0000	-0.1500	2.4000	1.59000	11.8400	
1.0000	-0.0188	0.3000	0.1988	1.4800	1.4800
	0.1241	0.0761	0.1973	0.3975	0.3975
	1.0000	0.6132	1.5898	3.2031	3.2030
		0.2151	0.3008	0.5160	0.5160
		1.0000	1.3984	2.3989	2.3984
			0.1143	0.1143	

Calculate index of determination, r^2 , and correlation coefficient, r , by (6):

$$r^2 = \frac{1.1647 - 0.1143}{1.1647} = 0.902$$

$$r = \sqrt{0.902} = 0.950$$

Compute regression coefficients by (7) and (8):

b_1 (psi/% H_2O) = -20.69

b_2 (psi/day) = 0.73

b_3 (psi/% lime) = 13.98

(These values are reported for moisture, time, and lime for Exum/lime in Table 21.)

Establish regression equation by (10):

$$\text{psi} = 356 - 20.69\ (\%\ H_2O) + 0.73\ (\text{days}) + 13.98\ (\%\ \text{lime})$$

Under the experimental moisture conditions, the equation becomes (b) plotted in Figure 23.

$$\text{psi} = 4 + 0.73\ (\text{days}) + 13.98\ (\%\ \text{lime})$$

Compute inverse matrix (11):

$$\begin{vmatrix} 0.5790 & 1.0396 & -1.4482 \\ & 9.8061 & -2.8508 \\ & & 4.6490 \end{vmatrix}$$

Determine actual values of diagonal terms by (16):

$$c_{11} = 0.5790$$

$$c_{22} = 0.00098061$$

$$c_{33} = 0.046490$$

Compute residual mean square by (17):

$$RMS = \frac{1,143}{11 - 4} = 163.2857$$

Compute standard deviations of regression coefficients by (18):

$$SD_1 \ (\% \ H_2O) = 9.72$$

$$SD_2 \ (\text{days}) = 0.40$$

$$SD_3 \ (\% \ \text{lime}) = 2.76$$

(These values are reported for Exum/lime in Table 31.)

Compute ratios (t) of regression coefficients to standard deviations by (19):

$$t_1(\% \ H_2O) = 2.13$$

$$t_2(\text{days}) = 1.82$$

$$t_3(\% \ \text{lime}) = 5.07$$

At seven degrees of freedom (11 - 4), the value of "Student-t" at the 90% confidence level is 1.89. At the 95% level, it is 2.36; at the 99% level, it is 3.50; and at the 99.9% level, the "Student-t" value

is 5.41. Thus, the moisture coefficient is significant at the 90% confidence level; the time coefficient is not significant; and the lime coefficient is significant at the 99% level.

Exum/PG2

Raw data generated from Exum/PG2 specimens are used in conjunction with those obtained from the untreated soil specimens in a manner identical with the procedure described above for Exum/lime. The raw data for Exum/PG2 specimens are (% H_2O, days, % PG2, psi):

(16, 1, 6, 26)	(17, 28, 9, 31)
(17, 7, 6, 29)	(17, 28, 9, 29)
(18, 14, 6, 29)	(18, 1, 12, 28)
(17, 28, 6, 29)	(18, 7, 12, 30)
(17, 28, 6, 28)	(18, 14, 12, 26)
(18, 1, 9, 28)	(18, 28, 12, 24)
(17, 7, 9, 30)	(19, 28, 12, 18)
(18, 14, 9, 26)	

$\Sigma y = \Sigma$ psi $= 411$ $\quad \Sigma y^2 = \Sigma$ psi$^2 = 11{,}405$

$\Sigma x_1 = \Sigma$ % $H_2O = 263$ $\quad \Sigma x_1^2 = \Sigma$ % $H_2O^2 = 4{,}619$

$\Sigma x_2 = \Sigma$ days $= 234$ $\quad \Sigma x_2^2 = \Sigma$ days$^2 = 5{,}442$

$\Sigma x_4 = \Sigma$ % PG2 $= 135$ $\quad \Sigma x_4^2 = \Sigma$ % PG2$^2 = 1{,}305$

$\Sigma x_1 x_2 = \Sigma$ % $H_2O \cdot$ days $= 4{,}112$

$\Sigma x_1 x_4 = \Sigma$ % $H_2O \cdot$ % PG2 $= 2{,}385$

$\Sigma x_2 x_4 = \Sigma$ days $\cdot$ % PG2 $= 2{,}106$

$\Sigma x_1 y = \Sigma$ % $H_2O \cdot$ psi $= 7{,}188$

$\Sigma x_2 y = \Sigma$ days $\cdot$ psi $= 6{,}291$

$\Sigma x_4 y = \Sigma$ % PG2 $\cdot$ psi $= 3{,}654$

n = population = 15

Add Exum/PG2 values to corresponding untreated soil values:

$\Sigma y = \Sigma$ psi $= 573$ $\quad\quad$ $\Sigma y^2 = \Sigma$ psi$^2 = 16{,}663$

$\Sigma x_1 = \Sigma$ % $H_2O = 344$ $\quad\quad$ $\Sigma x_1^2 = \Sigma$ % $H_2O^2 = 5{,}932$

$\Sigma x_2 = \Sigma$ days $= 312$ $\quad\quad$ $\Sigma x_2^2 = \Sigma$ days$^2 = 7{,}256$

$\Sigma x_4 = \Sigma$ % PG2 $= 135$ $\quad\quad$ $\Sigma x_4^2 = \Sigma$ % PG2$^2 = 1{,}305$

$\Sigma x_1 x_2 = \Sigma$ % $H_2O \cdot$ days $= 5{,}374$

$\Sigma x_1 x_4 = \Sigma$ % $H_2O \cdot$ % PG2 $= 2{,}385$

$\Sigma x_2 x_4 = \Sigma$ days $\cdot$ % PG2 $= 2{,}106$

$\Sigma x_1 y = \Sigma$ % $H_2O \cdot$ psi $= 5{,}932$

$\Sigma x_2 y = \Sigma$ days $\cdot$ psi $= 8{,}802$

$\Sigma x_4 y = \Sigma$ % PG2 $\cdot$ psi $= 1{,}305$

n = population = 15 + 5 = 20

Establish matrix (1):

$$\left[\begin{array}{cccc|} 15.2000 & 7.6000 & 63.0000 & -45.6000 \\ & 2{,}388.8000 & 0.0000 & -136.8000 \\ & & 393.7500 & -213.7500 \\ & & & 246.5500 \end{array}\right]$$

Exponents in matrix (2):

$q_1 = -1$, $q_2 = -2$; $q_4 = -1$; $p = -1$

Compute working matrices (3) and (4):

$$\left[\begin{array}{cccc|} 0.1520 & 0.0076 & 0.6300 & -0.4560 & 0.3336 \\ & 0.2389 & 0.0000 & -0.1368 & 0.1097 \\ & & 3.9375 & -2.1375 & 2.4300 \\ & & & 2.4655 & -0.2648 \end{array}\right]$$

Derive matrix (5):

0.1520	0.0076	0.6300	-0.4560	0.3336	
1.0000	0.0500	4.1447	-3.0000	2.1947	2.1947
	0.2385	-0.0315	-0.1140	0.0930	0.0930
	1.0000	-0.1321	-0.4780	0.3899	0.3899
		1.3222	-0.2626	1.0596	1.0596
		1.0000	-0.1986	0.8014	0.8014
			0.9908	0.9909	

Calculate index of determination, r^2 , and correlation coefficient, r , by (6):

$$r^2 = \frac{2.4655 - 0.9908}{2.4655} = 0.598$$

$$r = \sqrt{0.598} = 0.773$$

Compute regression coefficients by (7) and (8):

b_1 (psi/% H_2O) = -2.15

b_2 (psi/days) = -0.05

b_4 (psi/% PG2) = -0.20

(These values are reported for moisture, time, and sulfate waste for Exum/PG2 in Table 21.)

Establish regression equation by (10):

psi = 68 - 2.15 (% H_2O) - 0.05 (days) - 0.20 (% PG2)

Under the experimental moisture conditions, the equation becomes (c) plotted in Figure 23.

psi = 31 - 0.05 (days) - 0.20 (% PG2)

Compute inverse matrix (11):

$$\begin{vmatrix} 19.6229 & -4.6244 & -3.1396 \\ & 4.2061 & 0.0999 \\ & & 0.7563 \end{vmatrix}$$

Determine actual values of diagonal terms by (16):

$c_{11} = 0.196229$

$c_{22} = 0.00042061$

$c_{44} = 0.007563$

Compute residual mean square by (17):

$$RMS = \frac{99.08}{20 - 4} = 6.1925$$

Compute standard deviations of regression coefficients by (18):

SD_1 (% H_2O) = 1.10

SD_2 (days) = 0.05

SD_4 (% PG2) = 0.22

(These values are reported for Exum/PG2 in Table 31.)

Compute ratios (t) of regression coefficients to standard deviations by (19):

t_1 (% H_2O) = 1.95

t_2 (days) = 1.00

t_4 (% PG2) = 0.91

At 16 degrees of freedom (20 - 4), the value of "Student-t" at the 90% confidence level is 1.75. It is 2.12 at the 95% confidence level. Therefore, the time and PG2 regression coefficients are not significant. The moisture coefficient is significant at the 90% level.

Exum/PG2/Lime

The last set of data is concerned with strengths developed by the Exum/PG2/lime system. Raw data gathered from specimens containing both PG2 and lime are used in conjunction with those obtained for untreated soil, soil/lime, and soil/sulfate waste. The raw data for Exum/PG2/lime specimens are (% H_2O, days, % lime, % PG2, psi):

(19, 1, 6, 6, 53)	(23, 1, 6, 12, 46)
(20, 1, 6, 6, 67)	(23, 1, 6, 12, 58)
(20, 1, 6, 6, 57)	(23, 1, 6, 12, 52)
(20, 7, 6, 6, 146)	(23, 7, 6, 12, 133)
(20, 7, 6, 6, 115)	(22, 7, 6, 12, 131)
(20, 7, 6, 6, 171)	(23, 7, 6, 12, 114)
(20, 28, 6, 6, 335)	(23, 28, 6, 12, 260)
(20, 28, 6, 6, 330)	(22, 28, 6, 12, 255)
	(33, 28, 6, 12, 44)

$\Sigma y = \Sigma$ psi $= 2,367$ $\quad \Sigma y^2 = \Sigma$ psi$^2 = 485,985$

$\Sigma x_1 = \Sigma$ % $H_2O = 374$ $\quad \Sigma x_1^2 = \Sigma$ % $H_2O^2 = 8,392$

$\Sigma x_2 = \Sigma$ days $= 188$ $\quad \Sigma x_2^2 = \Sigma$ days$^2 = 4,220$

$\Sigma x_3 = \Sigma$ % lime $= 102$ $\quad \Sigma x_3^2 = \Sigma$ % lime$^2 = 612$

$\Sigma x_4 = \Sigma$ % PG2 $= 156$ $\quad \Sigma x_4^2 = \Sigma$ % PG2$^2 = 1,584$

$\Sigma x_1x_2 = \Sigma$ % $H_2O \cdot$ days $= 4,328$

$\Sigma x_1x_3 = \Sigma$ % $H_2O \cdot$ % lime $= 2,244$

$\Sigma x_1x_4 = \Sigma$ % $H_2O \cdot$ % PG2 $= 3,534$

$\Sigma x_2x_3 = \Sigma$ days $\cdot$ % lime $= 1,128$

$\Sigma x_2x_4 = \Sigma$ days $\cdot$ % PG2 $= 1,776$

$\Sigma x_3x_4 = \Sigma$ % lime $\cdot$ % PG2 $= 936$

$\Sigma x_1y = \Sigma$ % $H_2O \cdot$ psi $= 50,620$

$\Sigma x_2y = \Sigma$ days $\cdot$ psi $= 40,275$

$\Sigma x_3 y$ = Σ % lime · psi = 14,202

$\Sigma x_4 y$ = Σ % PG2 · psi = 20,760

n = population = 17

Add Exum/PG2/lime values to corresponding values for untreated soil, Exum/lime, and Exum/PG2.

Σy = Σ psi = 3,464 Σy^2 = Σ psi^2 = 551,818

Σx_1 = Σ % H_2O = 824 Σx_1^2 = Σ % H_2O^2 = 16,198

Σx_2 = Σ days = 605 Σx_2^2 = Σ days^2 = 13,975

Σx_3 = Σ % lime = 138 Σx_3^2 = Σ % lime^2 = 828

Σx_4 = Σ % PG2 = 291 Σx_4^2 = Σ % PG2^2 = 2,889

$\Sigma x_1 x_2$ = Σ % H_2O · days = 11,536

$\Sigma x_1 x_3$ = Σ % H_2O · % lime = 2,880

$\Sigma x_1 x_4$ = Σ % H_2O · % PG2 = 5,919

$\Sigma x_2 x_3$ = Σ days · % lime = 1,758

$\Sigma x_2 x_4$ = Σ days · % PG2 = 3,882

$\Sigma x_3 x_4$ = Σ % lime · % PG2 = 936

$\Sigma x_1 y$ = Σ % H_2O · psi = 69,629

$\Sigma x_2 y$ = Σ days · psi = 59,654

$\Sigma x_3 y$ = Σ % lime · psi = 17,346

$\Sigma x_4 y$ = Σ % PG2 · psi = 24,414

n = population = 17 + 5 + 6 + 15 = 43

Establish matrix (1):

407.8605	-57.4884	235.5349	342.6279	3,249.0930
	5,462.7907	-183.6279	-212.3023	10,916.3256
		385.1163	2.0930	6,228.9767
			919.6744	971.5814
				272,764.6047

Exponents for matrix (2):

$q_1 = -1$; $q_2 = -2$; $q_3 = -1$; $q_4 = -1$; $p = -2$

Compute working matrices (3) and (4):

4.0786	-0.0575	2.3553	3.4263	3.2490	13.0517
	0.5463	-0.1836	-0.2123	1.0916	1.1845
		3.8512	0.0209	6.2290	12.2728
			9.1967	0.9716	13.4032
				27.2765	38.8177

Derive matrix (5):

4.0786	-0.0575	2.3553	3.4263	3.2490	13.0517	
1.0000	-0.0141	0.5775	0.8401	0.7966	3.2000	3.2001
	0.5455	-0.1504	-0.1640	1.1374	1.3685	1.3685
	1.0000	-0.2757	-0.3006	2.0851	2.5087	2.5088
		2.4495	-2.0030	4.6664	5.1131	5.1129
		1.0000	-0.8177	1.9050	2.0874	2.0873
			4.6311	2.3999	7.0315	7.0310
			1.0000	0.5182	1.5183	1.5182
				12.1836	12.1831	

Calculate index of determination, r^2 , and correlation coefficient, r , by (6):

$$r^2 = \frac{27.2765 - 12.1836}{27.2765} = 0.553$$

$$r = \sqrt{0.553} = 0.744$$

Compute regression coefficients by (7) and (8):

b_1 (psi/% H_2O) = -9.43

b_2 (psi/day) = 2.88

b_3 (psi/% lime) = 23.29

b_4 (psi/% PG2) = 5.18

(These values were reported for moisture, time, lime, and sulfate waste for Exum/PG2/lime in Table 21.)

Establish regression equation by (14):

$$\text{psi} = 111 - 9.43\ (\%\ H_2O) + 2.88\ (\text{days}) + 23.29\ (\%\ \text{lime}) + 5.18\ (\%\ \text{PG2})$$

Under the experimental moisture conditions, the equation becomes (d) in Figure 23.

$$\text{psi} = -70 + 2.88\ (\text{days}) + 23.29\ (\%\ \text{lime}) + 5.18\ (\%\ \text{PG2})$$

Compute inverse matrix (11):

$$\left|\begin{array}{cccc} 0.7473 & -0.1869 & -0.4643 & -0.2817 \\ & 1.9239 & 0.2053 & 0.1136 \\ & & 0.5523 & 0.1765 \\ & & & 0.2159 \end{array}\right|$$

Determine actual values of diagonal terms by (16):

$c_{11} = 0.007473$

$c_{22} = 0.00019239$

$c_{33} = 0.005523$

$c_{44} = 0.002159$

Compute residual mean square by (17):

$$RMS = \frac{121,836}{43 - 5} = 3,206.2105$$

Compute standard deviations of regression coefficients by (18):

SD_1 (% H_2O) = 4.89

SD_2 (days) = 0.79

SD_3 (% lime) = 4.21

SD_4 (% PG2) = 2.63

(These values are reported for Exum/PG2/lime in Table 31.)

Compute ratios (t) of regression coefficients to standard deviations by (19):

t_1 (% H_2O) = 1.93

t_2 (days) = 3.65

t_3 (% lime) = 5.53

t_4 (% PG2) = 1.97

At 38 degrees of freedom (43 - 5), the value of "Student-t" at the 90% confidence level is 1.69. The "Student-t" value at the 95% confidence level is 2.03; it is 2.71 at the 99% level; and 3.57 at the 99.9% level. Thus, the moisture and PG2 regression coefficients for the Exum/PG2/lime system are significant at the 90% level, whereas the curing time and lime coefficients are significant at the 99.9% level.

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